INVESTIGATION AND EXPLOITATION
OF SNOWFIELD SITES

Malcolm Mellor

January 1969

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PREFACE

This monograph is the second of five on *Snow Engineering: Construction.* They summarize many years of development in site studies, laboratory work and excavation and construction techniques almost entirely the work of CRREL (Cold Regions Research and Engineering Laboratory), U.S. Army Terrestrial Sciences Center (USA TSC).

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CONTENTS

ILLUSTRATIONS

iv   **CONTENTS (Cont'd)**

                        ILLUSTRATIONS (Cont'd)

                            TABLES

EDITOR'S FOREWORD

Cold Regions Science and Engineering consists of a series of monographs written by specialists to summarize existing knowledge and provide selected references on the cold regions, defined here as those areas of the earth where operational difficulties due to subfreezing temperatures may occur.

Sections of the work are being published as they become ready, not necessarily in numerical order but fitting into this plan, which may be amended as the work proceeds:

I. Environment

A. General – Characteristics of the cold regions
1. Selected aspects of geology and physiography of the cold regions
2. Permafrost (Perennially frozen ground)
3. Climatology
a. Climatology of the cold regions. Introduction, and Northern Hemisphere I.
b. Climatology of the cold regions. Northern Hemisphere, II.
c. Climatology of the cold regions. Southern Hemisphere.
d. Radioactive fallout in northern regions.
4. Vegetation
a. Patterns of vegetation in cold regions
b. Regional descriptions of vegetation in cold regions
c. Utilization of vegetation in cold regions
B. Regional
1. The Antarctic ice sheet
2. The Greenland ice sheet

II. Physical Science

A. Geophysics
1. Heat exchange at the ground surface
2. Exploration geophysics in cold regions
a. Seismic exploration in cold regions
b. Electrical, magnetic and gravimetric exploration in cold regions
B. Physics and mechanics of snow as a material
C. Physics and mechanics of ice
1. Snow and ice on the earth's surface
2. Ice as a material
a. Physics of ice as a material
b. Mechanics of ice as a material
3. The mechanical properties of sea ice
4. Mechanics of a floating ice sheet
D. Physics and mechanics of frozen ground
1. The freezing process and mechanics of frozen ground
2. The physics of water and ice in soil

F.J. SANGER

INVESTIGATION AND EXPLOITATION OF SNOWFIELD SITES

by

Malcolm Mellor

SITE INVESTIGATION AND MATERIAL TESTING

Introduction

Major construction on permanent snowfields is comparatively rare, so that each project involves significant engineering innovation and thorough site investigation becomes an essential prerequisite. A wide variety of techniques is available for site exploration and snow testing, but few of these techniques are standardized, and most of them demand considerable knowledge and experience for dependable execution and interpretation.

Climatic Data

Climatic records are available for only a few scattered points on the ice sheets of Greenland and Antarctica, and unless the new construction site is close to a former base no records of direct observations are obtainable. Since no significant climatic summary can be compiled from short-term observations, it is usually necessary to resort to indirect methods to gain meteorological data for design purposes.

A first approximation can be arrived at by interpolation from records of sites occupied in the past, and this can be followed up by a check of certain climatic indicators at the site itself. In a dry-snow area, the temperature measured about 30 ft below the surface gives a good approximation of the mean annual temperature. Annual snow accumulation, a more significant parameter than total precipitation, can be determined from a study of snow stratigraphy in pits or cores. Wind direction may be indicated by the orientation of snow surface features: small, sharp-edged sastrugi will be aligned mainly along the direction of the prevailing "dry" wind; whereas large, rounded snow dunes may show the direction of the cyclonic winds which bring most of the precipitation. The height of sastrugi in a given area is sometimes taken as an indicator of maximum wind speed for comparative purposes.

Pit Examination

Observations on the wall of a pit offer a ready means of studying the snow layers underlying a construction site. Long trenches bulldozed through the snow are preferable to narrow pits for examination of the upper layers, since they reveal a more representative section. Trenches can be deepened to about 20 ft in selected spots without much trouble, using pick-and-shovel methods to dig pits. Deep pits, to a depth of 100 ft or more, need more careful preparation: a good method is to dig them at about 15° from the vertical, with ladders pegged into the inclined wall and a bucket-hauling track left free. Stages should be provided every 15 ft or so.

Visual observation of a clean pit wall reveals gross features of the snow stratigraphy, such as ice bands and lenses, wind and radiation crusts, dust horizons, prominent layers of depth hoar,

etc. Stratigraphic features can be exaggerated and made clearer by lightly scouring the pit wall with a whisk broom, by spraying the snow with liquid dye, or by "flaming" the pit wall. Flaming is a technique whereby a controlled oil fire is allowed to play on the snow, etching it by differential melting and blackening the surface.

After visible features of the snow profile have been recorded, measurements of density, temperature, grain size, and hardness are made; samples may then be cut for further testing in the snow laboratory. Average grain size can be measured in a pit by scanning the snow of different layers with a transparent graticule or pocket counting glass (a hand lens with an etched graticule). It can also be estimated by flaking grains onto a laminated card covered with 1-mm-grid graph paper. Hardness may be measured on the pit wall with a small penetrometer, such as the Canadian hardness gage supplied in USA CRREL snow kits (see below). Rough checks of snow hardness can be made by probing the snow with fingers, pencil and knife according to the procedure outlined in the "Simplified field classification of natural snow types" given in Table I.[26] The methods for measuring density and temperature are described below.

From a snow profile, annual accumulation can be deduced (although considerable experience is necessary for reliable interpretation) and a preliminary assessment of the material's engineering properties can be made. Pit data from a cold (melt-free) snowfield can be analyzed to give natural settlement rates of various layers, compactive viscosities and other useful parameters.

Additional information on the study of snow pits is given in CRSE Monograph II-C1.[12]

Table I.[26] Simplified field classification of natural snow types for engineering purposes.

Grain nature	Code
1. New snow (original crystal forms such as stars, plates, prisms, needles and graupel granules are recognizable)	Fa
2. Old snow, granular fine-grained (mean diameter is less than approximately 2 mm - like table salt)	Db
3. Old snow, granular coarse-grained (mean diameter is larger than approximately 2 mm - like coarse sand)	Dd
4. Depth hoar (cup-shaped crystals 3 to 10-mm diameter, usually found near the bottom of a seasonal snow pack)	De.

Hardness (use gloves)	
1. Very soft (closed fist)*	Ka
2. Soft (4 fingers)**	Kb
3. Medium hard (1 finger)**	Kc
4. Hard (pencil)**	Kd
5. Very hard (knife-blade)**	Ke

Wetness (use gloves)	
1. Dry (snowball cannot be made)	Wa
2. Moist (does not obviously contain liquid water, but snowball can be made)	Wc
3. Wet (obviously contains liquid water)	Wd
4. Slushy (water can be easily pressed out)	We

*Sideways movement possible
**The object indicated (but not the foregoing one) can be pushed into the snow without considerable effort.

Core Drilling

For core drilling in snow, an effective hand coring auger is available. This is a stainless steel auger, 3 in. ID, 4¼ in. OD, and 39 in. (1 m) long, with a special cutting head designed for rapid cutting in snow and ice. The auger lifts 3-in.-diam cores in lengths of about 20 in., and with its extension rods (each 1 m long) it is capable of coring to depths of 100 ft or more. The auger is normally turned by means of a cranked wood brace or by a T-bar, although a hand-held motor can be used. When the auger is being used for deep coring, a hoisting tripod is rigged over the hole and split collets fitted into a hole-top plate hold the drill string during coupling. The auger is produced for USA CRREL and is obtainable commercially. It packs into carrying cases for easy transport.

The USA CRREL hand coring auger is probably adequate for most exploration coring requirements in snow, but for deeper coring, which is strictly ice drilling rather than snow drilling, special mechanical and thermal methods have been developed. These are described on pages 39-40 and details of the conventional rotary method are given in USA SIPRE Technical Reports 60[19] and 70[21]

Snow cores are marked with a felt-tipped marking pen and packed in strong cardboard cylinders for transport to the laboratory. There they are laid out in sequence in a V-trough, examined, and prepared for further testing.

Field Measurements

Snow temperature

Temperatures in snow layers close to the surface (the top 10 ft or so) are usually measured by inserting the stems of bimetal dial thermometers into the wall of a pit which is shaded from direct sunlight. The thermometer stems are pushed tightly into holes punched with a steel rod, and the side of the pit which is shaded from the sun is selected for the measurements. Suitable thermometers are included in the USA CRREL snow-density kit.

Temperatures at depths greater than about 10 ft are normally measured by some form of remote-indicating thermometer inserted in a vertical borehole. Thermohms, thermistors and thermocouples have all been used with success. The degree of precision varies with the data requirements; in some cases simple instruments reading to one degree are adequate; in other cases high precision is called for, and elaborate devices reading to one-hundredth of a degree or less are used. Exploratory temperature profiles are often measured in open holes; but more permanent temperature wells, such as those beneath foundations, are backfilled with a string of temperature elements in place. If temperatures are measured in open holes, the holes should not have metal casing, since this can disturb the thermal regime by transmitting surface temperature fluctuations to depth, making readings unreliable.

In areas free from appreciable melting, temperatures in the top 2 or 3 ft of snow vary from day to day as air temperatures change; seasonal surface temperature variations are detectable to a depth of 30 or 40 ft, and below 40 ft temperatures remain steady with time. The range of temperature variation decreases with increasing depth, and the amplitude of variations, as mentioned before, reduces to zero at about 40-ft depth (see CRSE Monograph III-A1,[1] Chapter VI). Below 40 ft there is a gradual change of temperature with increasing depth. On polar ice sheets there is usually a drop in temperature with increasing depth, at least for some hundreds of feet, but on ice shelves and small glaciers the temperature usually increases with depth.

Density

   Direct measurements of snow density are usually made by cutting cylindrical samples with a special tube, of known weight and volume, and weighing the tube and sample on a portable spring balance. Sampling tubes are driven into the undisturbed snow mass and carefully broken free; the ends of the samples are then trimmed flush with the ends of the tubes. Rubber caps are placed over the ends of the tubes to retain the samples.

   A special density-measuring kit that allows measurements to be made easily and rapidly has been produced by USA CRREL. The stainless steel sample tubes (5.8 cm ID, 18.9 cm long) have a volume of 500 cm^3 and a uniform weight. The pointer of the weighing scale can be preset to read zero with an empty tube on the pan, so that the weight of the snow is read directly. The scale reading is multiplied by 2 and, with the position of the decimal point adjusted mentally, this gives the density in g/cm^3 (or the specific gravity) directly. Figure 1 shows the USA CRREL snow-density kit.

   Cold high-density snow can be too hard for a sampling tube to penetrate. In this case, rectangular snowblocks are sawn out and carefully measured to give their volumes. The blocks are then weighed. A miter box facilitates the cutting of these blocks.

   The density of a core sample is checked by simply sawing off a length of core, calculating its volume, and weighing it.

   Experimental bore-logging devices for continuous recording of snow density *in situ* have been built. They are based on absorption or back-scatter phenomena for nuclear radiation or upon related radiation principles. So far the accuracy and resolution of these instruments have been inadequate for detailed site exploration.
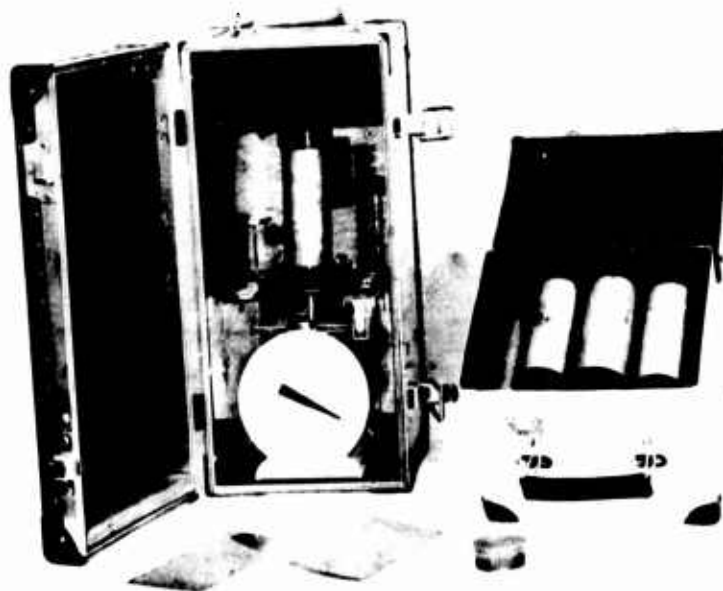
Figure 1. USA CRREL snow-density kit. The kit includes a spring balance with adjustable zero setting, 500-cm^3 stainless steel sample tubes with rubber end caps, and bimetal dial thermometers.
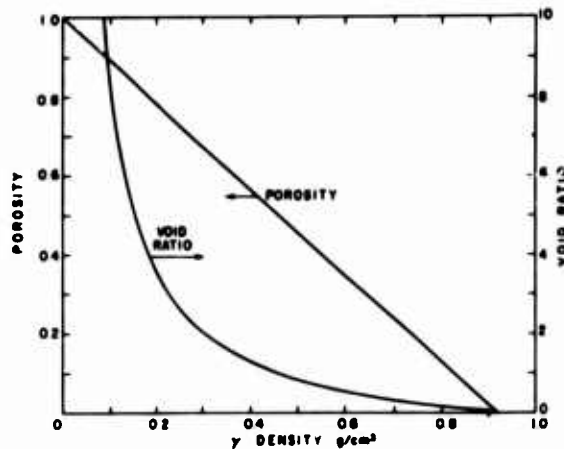
Figure 2. Porosity and void ratio as functions of bulk density for dry snow.

Bulk density γ may be expressed in alternative forms as porosity n or void ratio r according to the following relations:

$$\text{Porosity} \quad n = \frac{\gamma_{ice} - \gamma}{\gamma_{ice}} = 1 - 1.09\gamma \qquad (1)$$

$$\text{Void ratio} \quad r = \frac{\gamma_{ice} - \gamma}{\gamma} = \frac{n}{1 - n} . \qquad (2)$$

Figure 2 gives a graphical conversion from density to porosity and void ratio.

Grain size

Both absolute grain size and grain-size distribution in a particular sample of snow may change with time as a result of sublimation and possibly surface diffusion. Grain-size data should therefore be treated with caution.

Optical scanning can be used to measure grain sizes, although the work involved may be tedious. If the snow is disaggregated (natural blowing snow, milled snow) a representative sample is caught on a slide and is measured promptly before the finest particles evaporate. If the snow is in a coherent mass it can be crumbled onto a slide, or a thin section can be cut with a plane or microtome after the snow has been saturated with aniline and frozen into a solid block (see CRSE Monograph II-C1[12]).

Sieve analysis has been used to classify both disaggregated snow and deposited snow. In the case of sintered deposited snow, the material is disaggregated prior to sieving by rubbing snow on snow. The adhesion between small ice particles makes it very difficult to sieve fine fractions at temperatures near the melting point. Adhesion decreases with decreasing temperature and, if possible, sieving should be carried out at temperatures below –20C. In ice-cap engineering studies[4] USA SIPRE used a dynamic sieve shaker with no. 10 to no. 120 sieves. The results were recorded on standard forms.

Grain size has also been measured by elutriation in cold liquids.

Air permeability tests

The air permeability of snow is used as a means of classifying snow types, and it is also measured to give data relating to ventilation and seepage problems. Experiments indicate that airflow through snow is laminar for velocities less than 5 cm/sec for fine-grained snow (less than 0.8-mm diam); 2 cm/sec for medium-grained snow (0.8-1.2-mm diam); and 1 cm/sec for coarser-grained snow. Under laminar flow conditions the USA SIPRE results[4] can be represented by the equation

$$K = 16.8 \frac{d^{1.63}nN}{N-n} \tag{3}$$

where K is air permeability, n is porosity, d is average grain size in mm, and N is the maximum porosity for the given particle shape.

Grain size can be estimated from initial permeability K_0 and initial porosity n_0 from the expression

$$d^{1.63} = \frac{K_0}{2.97} \frac{1}{n_0} . \tag{4}$$

Figures 3 a and b show two types of permeameters built for research purposes[5]. The type in Figure 3a gives flow rates of 0.06-0.8 cm³/sec by liquid displacement, and the type in Figure 3b is a constant-velocity permeameter which draws air through the sample by means of a piston at rates between 0.5 and 2000 cm³/sec. Both permeameters take samples in the standard USA CRREL snow tube (7.4 in. long × 2.28 in. ID).

Figure 4 shows an air permeameter which was used for site testing in Greenland[5]. A constant-speed piston provides the air flow; piston travel gives the quantity of air passed. Pressure difference is measured by a micromanometer filled with low-viscosity silicone fluid.

The density of samples is determined prior to permeability testing, and density can be converted to porosity by eq 1.

Hardness and bearing capacity

Rammsonde penetrometer. The Rammsonde is a device which has been widely used for rapid field measurements of penetration resistance. The incremental penetration of a spear-pointed rod produced by a series of controlled hammer blows gives a vertical profile of driving resistance. Penetration resistance measured by the Rammsonde correlates with shear strength, unconfined compressive strength and other penetration indices. The chief merits of the instrument are its simplicity and the reproducibility of its results. Unlike spring-loaded penetrometers, the Rammsonde gives results which do not vary greatly with individual operator technique, provided reasonable care is taken. Refinements of design and procedure have been proposed,[10][11] but so far they have not been generally adopted.

The Rammsonde consists of several hollow tube sections, each 1 kg in weight, 1 m long, 3 cm in diameter, and marked off in 1-cm graduations (Fig. 5, 6). The end of the leading tube bears a 60° conical point which expands to a diameter of 4 cm before tapering back to the tube. A metal rod, 60 cm long and graduated at 10-cm intervals, mounts on top of the penetrometer driving tubes and acts as a guide for the driving hammer (1-, 2- or 3-kg pierced cylindrical weights). A vertical profile of ram resistance is obtained by driving the Rammsonde down through the snow in increments and recording the penetration after each hammer blow (Fig. 7). An alternative method is to record the number of blows necessary to penetrate a fixed distance.

1 TANK TO MAINTAIN CONSTANT HEAD
2 FLOW REGULATOR VALVE
3 ON-OFF VALVE
4 ADAPTER TO HOLD SAMPLE TUBE
5 CONNECTION TO MANOMETER
6 WIRE MESH
7 STANDARD SAMPLE TUBE
8 AIRTIGHT WEIGHING BOTTLE
9 DRAIN ON-OFF VALVE
10 OVERFLOW TUBE
11 PUMP
12 EXCESS FLUID RESERVOIR
13 BALANCE. 5 KG, ACCURATE TO 1 G

a. Low airspeed   b. High airspeed
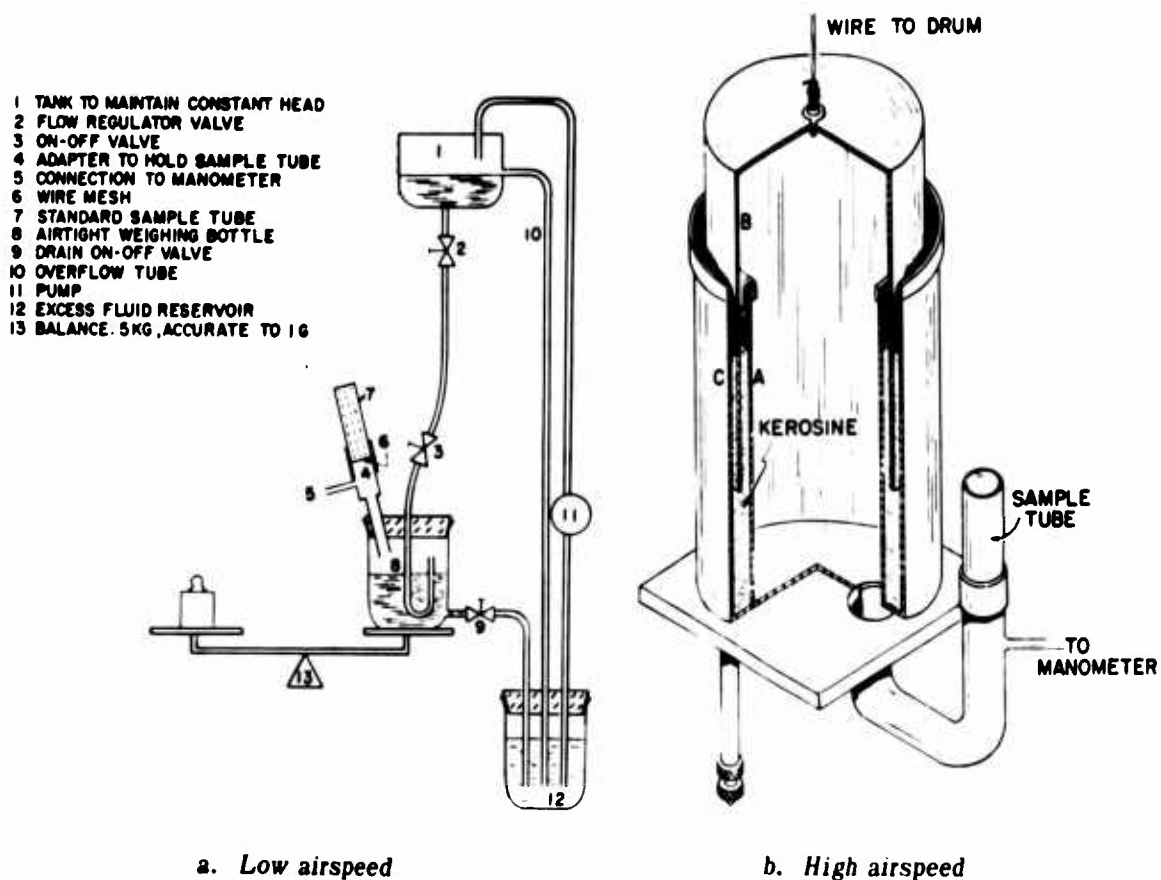
Figure 3. Schematic illustrations of two types of air permeameters for snow. (Bender[5].)
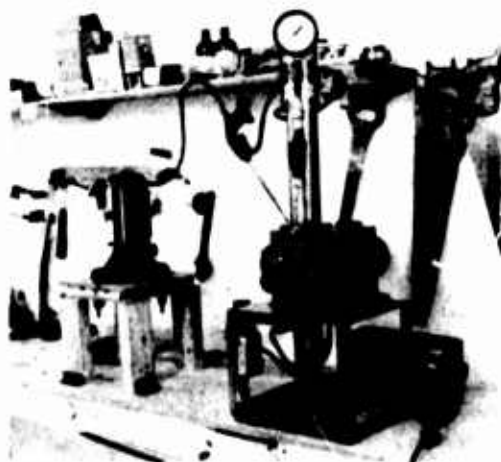
Figure 4. Air permeameter used for site
testing in Greenland.
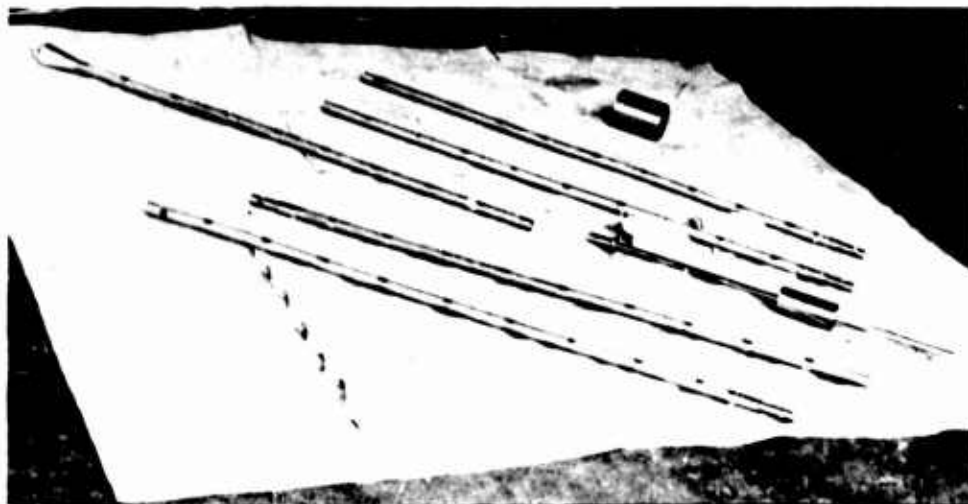
Figure 5. USA CRREL Rammsonde kit. The kit includes the spear-pointed sonde, drop-weights and guide rod, and calibrated extension rods.

Figure 7. Rammsonde in use.
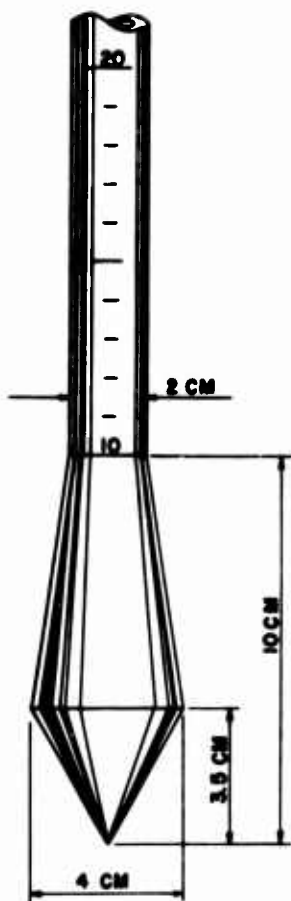
Figure 6. Detail of the point of the Rammsonde.

The following is a typical Rammsonde operating procedure:

1. Insert hammer guide in top of first section (which has cone point).

2. Let sonde hang vertically over snow surface by holding near top end, and gently lower until cone point touches snow surface.

3. Let go, but immediately grab sonde again to prevent its falling over (from here on, provide constant side guidance until sonde stands vertically by itself).

4. Read penetration.

5. Slip hammer on hammer guide until it touches shoulder with no pressure.

6. Release hammer.

7. Read penetration.

8. Start hammering by raising hammer on guide to desired height and letting it drop onto shoulder.

9. Read penetration after each hammer blow or (if very small) after a series of counted blows, all from the same drop height.

10. When sonde is close to total immersion in snow, remove guide with hammer, attach one length of tubing, and insert guide and hammer in top of new length.

11. Compute ram resistance according to the formula given below, and plot a vertical profile.

$$R = \frac{Pnh}{x} + qQ + P$$

R - ram number (kg)

h - height of fall (cm)

P - weight of hammer (kg)

x - penetration per n blows (cm)

n - number of blows

q - number of tube lengths

Q - weight of one tube (kg).

Ram resistance is usually plotted against depth as part of the stratigraphic profile for the site material. "Integrated Rammsonde profiles" are sometimes plotted to provide a site characteristic for comparative purposes: the total penetration energy

$$\sum_{0}^{x} R \Delta x$$

is plotted against depth x.

A wide variety of penetrometers has been used in snow, but no single one has won the wide acceptance accorded the Rammsonde. The chief difficulty with spring-loaded penetrometers (including proving-ring types) is that snow is too sensitive to loading rate for hand-loaded penetrometers to give consistent and reproducible results.

Canadian (National Research Council) "hardness" gage. The Canadian "hardness" gage is a small hand instrument for rapid field measurements of snow hardness. It has a spring-loaded plunger which is pressed against the snow, usually the vertical wall of a pit. The applied force necessary to cause collapse of the snow is read from a calibrated rod which emerges from the plunger barrel as the spring is stressed. Different discs can be attached to the end of the plunger so that the bearing area is 0.1, 1.0, or 100 cm^2. Two separate springs are available to permit measurements in the ranges 1-1000 g/cm^2 and 10-10,000 g/cm^2 with the various discs. "Hardness" is expressed as the nominal pressure to cause collapse (spring force divided by bearing area) in g/cm^2. The results are dependent to some extent on the size of plate used and on the rate of load application.

U.S. Army Waterways Ex eriment Station cone penetrometer (Vicksburg cone). This instrument forms the basis of the Army trafficability tests for both soils and snows, and index readings given by the apparatus have been correlated with the mobility requirements of a wide range of military vehicles.

The cone penetrometer consists of a 30° cone of 0.5-in^2 base area, an aluminum staff 18 in. to 36 in. long and ⅝-in. diam, a proving ring, a micrometer dial gage, and a handle (Fig. 8). When the cone is forced into the snow, the proving ring is deformed in proportion to the force applied. The force required to move the cone slowly through a given horizontal plane is indicated on the dial inside the ring. This force is considered to be an index of the shearing resistance of the snow and is called the cone index of the snow in the given plane. The range of the dial is 0 to 300; the standard soil proving ring deflects 0.1 in. at 150-lb load, but the special proving ring for snow deflects 0.1 in. at 50-lb load, giving a cone index reading of 100.

Proctor needle. The Proctor needle is a standard soil-mechanics instrument. It consists of a spring-loaded needle with a pressure-indicating scale on the handle, and it is forced into the snow manually. Several interchangeable needles for bearing plates of cross sections ranging from 0.05 to 1.00 in^2 are available for the instrument. The size of the plate or needle affects the results. The needle is short, so that measurements can be made only through a shallow layer; rate of loading depends on the operator.

Arctic-Desert-Tropic. The Arctic-Desert-Tropic penetrometer is a brass penetrometer weighing 5 lb with a circular contact area of 5 in^2. Two cylindrical brass weights, 5 and 10 lb, slide on the handle of the penetrometer. All three elements are graduated in inches so that penetration can be read directly. Static tests are carried out by holding the penetrometer just in contact with the surface, then releasing it. Dynamic tests are performed by dropping the penetrometer from a height of 12 in. Both static and dynamic tests are made with weights corresponding to 1-, 2-, and 4-psi static loading.

Drop-cone penetrometer. The drop-cone penetrometer is a 210-g metal cone fixed to the lower end of a graduated rod which slides vertically through a hole in the headplate of a tripod. The cone is dropped into the snow from a known height (in the range 0-40 cm) and the penetration is measured. Hardness is read from a chart similar to that shown in Figure 9. This graph refers to a 75° cone; if a 60° cone is employed the hardness readings are multiplied by 1.77, and if the cone angle is 90° the multiplying factor is 0.59.

California bearing ratio. CBR tests can be performed on snow to assess its probable value for supporting wheel and track loads and occasionally for other purposes when bearing capacity is important. Standard CBR equipment attached to a tractor is used, and the bearing plate is forced into the surface at a rate of about 0.2 in./min after an initial 2-psi seating load has been applied and relaxed. During a CBR test on snow there is apparently an elastic deformation up to a critical point, at which a collapse or plastic yield occurs. The stress at this initial yield point is taken as the bearing capacity of the snow. CBR tests can be used for comparing the capabilities of different snows, but results are not directly comparable with CBR values for soils.
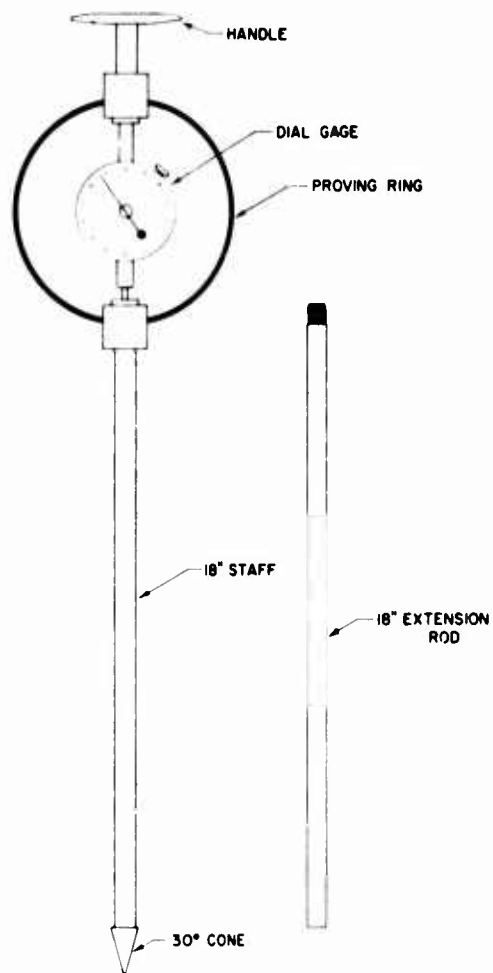
Figure 8. *U.S. Army Waterways Experiment Station cone penetrometer, or Vicksburg cone.*
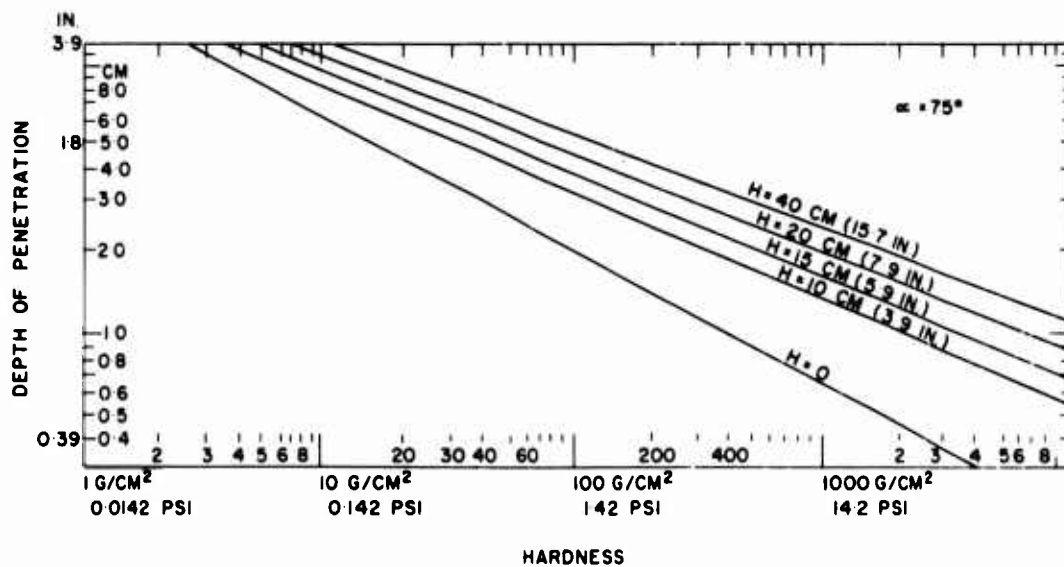
Figure 9. *Graph for evaluation of drop-cone penetrometer measurements.*

In-situ shear strength

Measurements of shear strength can be made *in situ* with shear vanes and shear boxes.

Simple shear vanes similar to the kind used in soils have been used in snow. Various dimensions have been tried (Fig. 10) but there is little significant variation of the results with vane size over a limited range? The vane is inserted into the snow at the end of a rod and is supported at the required test level by a surface plate. The vane is turned by means of a torque wrench, and the rupture stress σ_s is given by the relation:

$$M_{max} = \sigma_s 2\pi \left\{ r_o^2 h + \tfrac{1}{3}(r_o^2 - r_i^2)(2r_o + r_i) \right\} \qquad (5)$$

where M_{max} is the torque at failure, r_i and r_o are the inner and outer diameters of the vane respectively, and h is the vane height.

Another shear vane designed for use in snow gives a Mohr envelope when various normal pressures are applied to the shear surface? The vane consists of a tube with vanes at the lower end and provision for adding weights. The tube is turned by a torque wrench, and the shear resistance σ_s is given by the relation:

$$\sigma_s = \frac{2M_{max}}{\pi r^3} \qquad (6)$$

where M_{max} is the maximum torque and r is the tube radius. Measurements are repeated on the same type of snow for a range of normal pressures to give a Mohr envelope.

Very much more complicated shear vanes have been used in snow (see CRSE Monograph III-A4[10] for details), but they are of little interest for site investigation.

Simple shear boxes of the kind shown in Figure 11 are sometimes used in snow. Benches are cut in a pit wall and the box is used as indicated in the figure.
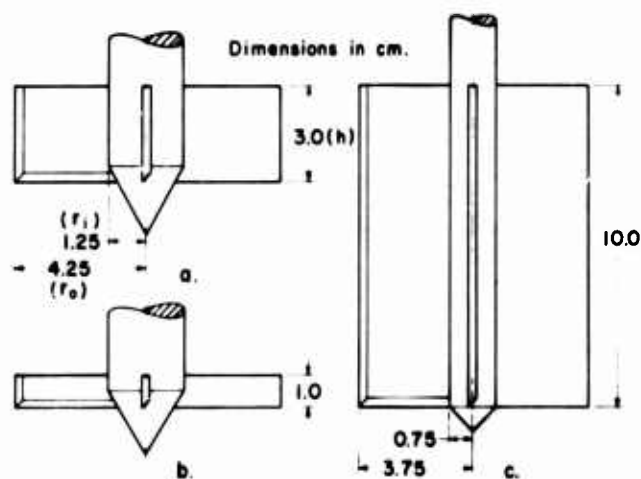
Figure 10. Simple shear vanes used in snow. (Keeler and Weeks?)
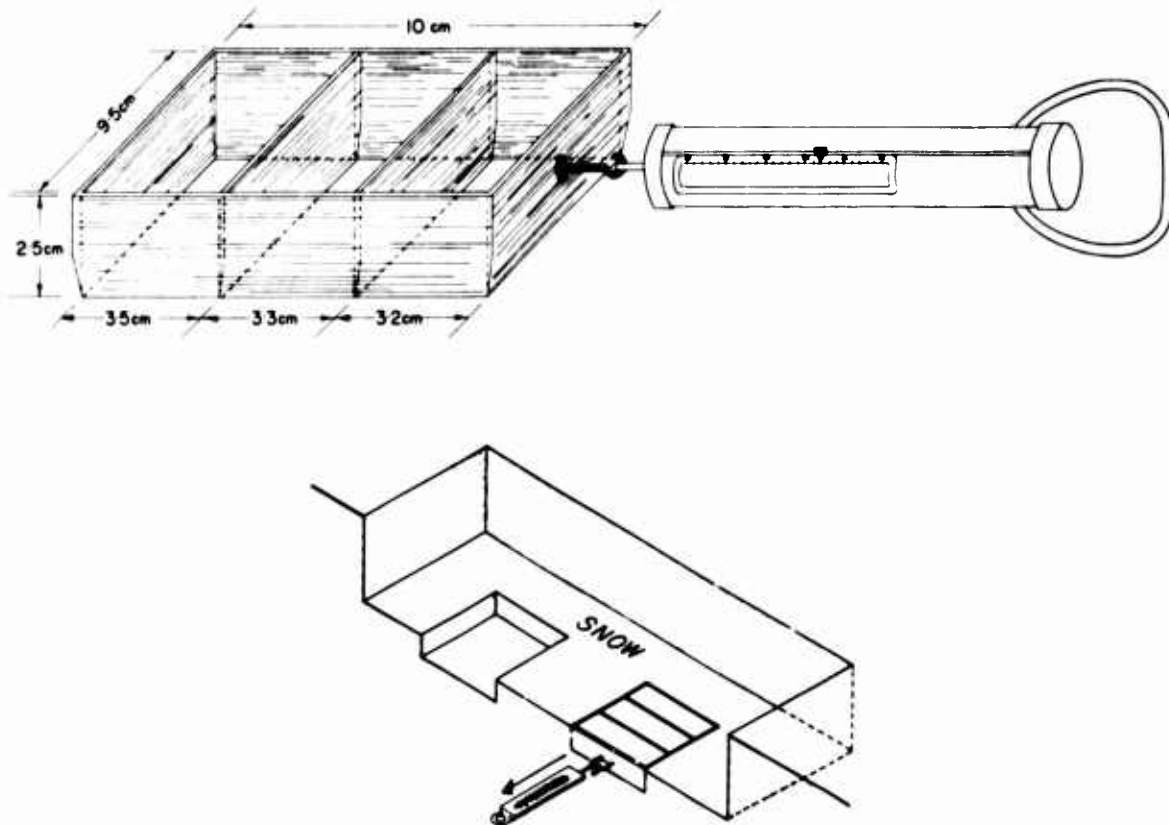
Figure 11. Simple shear box for making in-situ measurements on snow.

Both vanes and boxes are subject to criticism on the grounds that they define the shear surface and subject the snow to significant volumetric strain while shearing it. In the simple forms they are also liable to wide variations in loading rate. Nevertheless, they are cheap, easy to operate, and in most cases give acceptable results.

In-situ creep observations

Since snow deforms continuously under load, creep properties and stress/strain-rate relations are of prime importance for structural design.

Undisturbed site material on cold snowfields is creeping continuously under self-weight body forces. For any snow layer, the rate of change of density with time gives a measure of the creep rate, while the overburden pressure represents the applied stress.

Laboratory Strength Measurements

While strength measurements made under rapid loading conditions are of only limited value for structural design on ice caps, it is generally worthwhile to make such tests for comparative purposes.

It should always be recognized, however, that snow is highly sensitive to loading rate, so that "strength" is often no more than an arbitrary index of mechanical properties.

Tests made in the field laboratory are usually designed to utilize cylindrical samples which have been extracted from the snow mass either by means of the standard USA CRREL snow sampling tube (5.8 cm ID, 18.9 cm long) or by the USA CRREL 3-in. coring auger.

Unconfined compressive strength

To give meaningful data the unconfined compression test on snow should be made at rates of loading (or straining) sufficiently high to produce "brittle" failure under elastic conditions rather than "ductile" creep rupture. The loading conditions necessary to guarantee brittle failure have not been well defined for a wide range of snow types, but from limited data it seems that common presses tend to be too slow. As a practical guideline, it can be stated that press speeds ought to be from 6 to 10 in./min for typical samples 6 to 8 in. long. Lower press speeds may suffice for cold high-density snow, but they produce "barreling" in low-density snow or warm snow. An expedient way of speeding up the typical hand-loaded screw press is to remove the handcrank and drive the spindle with a ½-in. electric drill.

Cylindrical samples are cut to the required test length with a saw and their ends are trimmed in a miter box. The usual sample size is 5.8-cm-diameter and about 18 cm long (length should be about 3 times diameter). The sample density is checked by weighing, and the sample is brought to the required test temperature by exposure to the test laboratory temperature.

Hand-operated hydraulic presses have been used, but they tend to give a slow and jerky motion. Hand-cranked screw presses have proved to be quite satisfactory for dense snow, provided they are cranked at top speed. Motorized screw presses are entirely satisfactory for site testing as long as they are capable of driving the platens fast enough. For site test purposes (as opposed to research purposes), the most satisfactory load indication is given by a proving ring and dial micrometer, while a dial micrometer operating on the platens is usually sufficient as a strain indicator. The additional complication required for detailed stress/strain recording would not normally be justified in a routine engineering site investigation.

Figure 12. Motorized press making unconfined compression test on snow at a site in Greenland.

Tensile strength

Direct tensile tests are awkward to perform on snow because of the difficulty of sample preparation and the problems involved in attaching the specimen to the pulling device. Cylindrical samples of fairly dense snow have been tested by freezing metal end plates to the sample and feeding lead shot into a load pan at the low rate of 0.35 kg/cm² min, but this method has not been generally accepted.

The most satisfactory method for measuring the tensile strength of low-density snow is the centrifugal test. A notched sample is carried in a cylindrical tube (5.8 cm ID, 18.9 cm long), and the tube is spun about a central axis normal to the axis of symmetry. The rotational speed at which

the sample breaks is read from a tachometer, and the corresponding tensile stress on the rupture surface is given by a nomograph when the rotational speed and the sample mass are entered.

A convenient method for use on high-density snow is the ring tensile test. A short length of core or other cylindrical sample is cut, and a concentric hole is drilled down its center in a special jig. A compressive load is then applied normal to the axis of symmetry by means of a press and, if the loading is sufficiently rapid to produce a predominantly elastic response, the tensile strength σ_t is given by the relation:

$$\sigma_t = \frac{KP}{\pi r_o \ell} \tag{7}$$

where P is the compressive load at failure, ℓ is the sample length, r_o is the outside radius of the ring, and K is a concentration factor depending on the ratio of internal and external diameters of the ring.

In tensile strength tests the loading must be rapid in order to produce elastic response and minimize the dependence on loading rate or strain rate. For dense snow a loading rate of 0.5 kg/cm^2 sec has been found satisfactory.

Shear strength

Tests in single shear have been made with an apparatus similar in principle to soils shear boxes (Fig. 13). A cylindrical snow sample of standard size (5.8-cm diam) is introduced into a vertically oriented steel tube which is cut and free to shear at its midsection. Deadweight on top of the sample provides normal load across the shear plane, and the shear force is applied through a cable and pulley by a pan to which lead shot is added at a controlled rate.

A simple device for single shear with approximately zero normal stress is used by the Naval Civil Engineering Laboratory (NCEL). A short section of cylindrical core sample is placed in a carrying cylinder and is sheared by a pair of stepped "choppers" which are loaded from a press (Fig. 14). The apparatus clearly applies a rather severe moment to the sample, but it is said to be very satisfactory for field testing.

Double shear tests have been made by placing cylindrical snow samples in a three-section steel tube and shearing out the center section. In the USA CRREL apparatus the sample tube is designed to accept 3-in.-diam core in 12-in.-long sections. Axial load is applied by a manually loaded piston, with a dynamometer for measurement. The shear force is applied to the center section of the sample tube by means of a hand-loaded press with a proving ring and dial gage for measurement. In studies by USA SIPRE[6] the initial failure was disregarded and loading was maintained until the shear resistance dropped to zero. The loading rate was approximately 5 lb/in.^{2} sec (0.34 kg/cm^2 sec).

The shear strength of high-density snow has been measured in torsion by applying torque to 3-in.-diam snow cylinders. The apparatus is shown in Figure 15. It consists of a stationary frame which holds one end of the specimen, and a rotating frame to which is attached a spring balance and lever for measurement of torque. The ends of the sample are frozen into square blocks of snow slush for fitting into the apparatus. The method assumes elastic behavior in the specimen, so that rapid loading is necessary; in USA SIPRE studies a loading rate of 9 lb/in.^{2} sec was used. Shear strength, or torsional modulus of rupture, σ_s, is calculated from the relation:

$$\sigma_s = \frac{16 M_{max}}{\pi d^3} \tag{8}$$

where M_{max} is the applied torque at failure and d is the diameter of the test cross section.
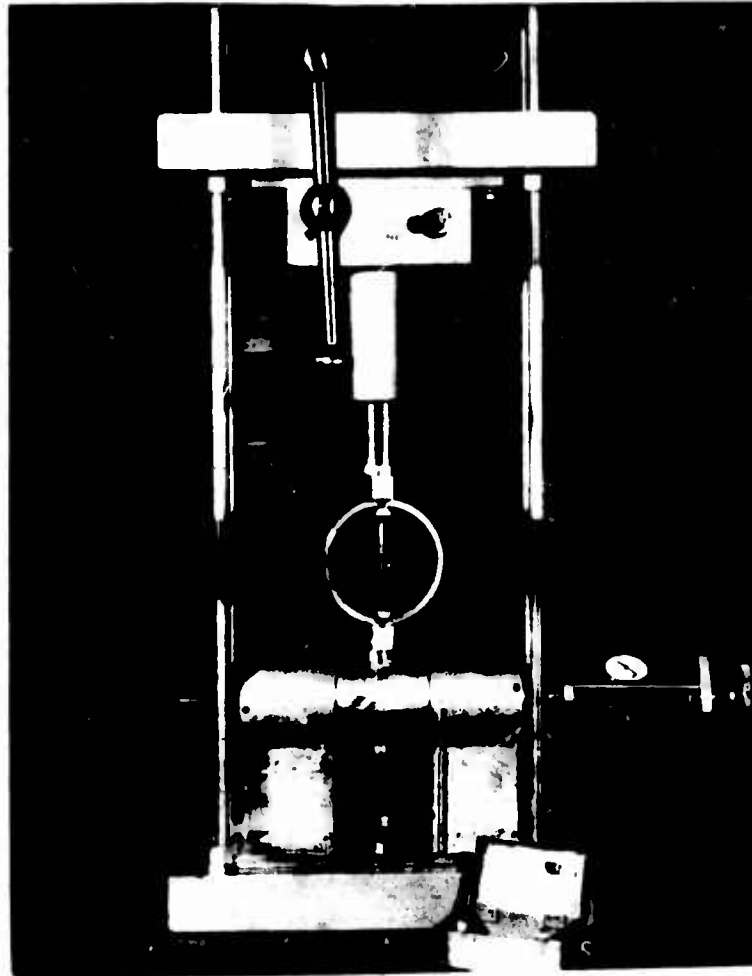
Figure 13. Double shear apparatus.
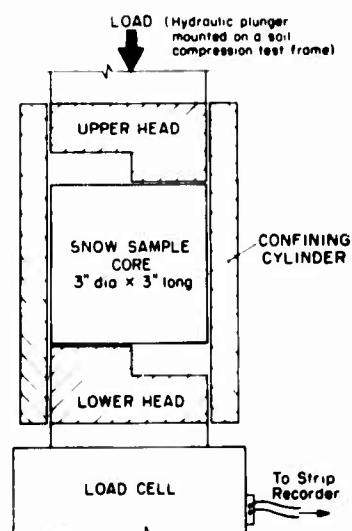
Figure 14. NCEL shear apparatus.
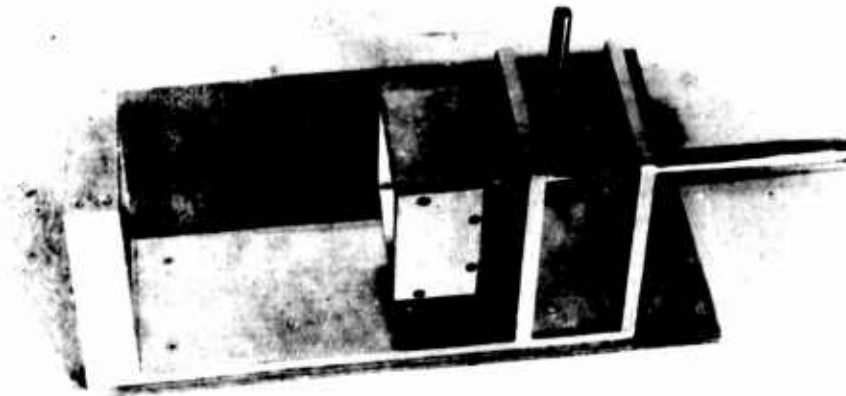
Figure 15. Apparatus for applying torque to snow samples.

When snow is sheared under a confining stress the results obtained must be treated with great caution. The applied normal stress produces time-dependent volumetric strain in the sample, and the material under test is actually being altered by the loading. The measured shear strength may very well depend upon the length of time during which the sample has been under the applied normal load.

Triaxial tests

Triaxial testing apparatus for snow has been built and used experimentally, but it has never been developed to a really satisfactory level. At the present time triaxial testing of snow cannot be considered as a routine site-investigation procedure for construction purposes.

Disaggregation tests

The energy of disaggregation, that is, the energy required to separate unit lume of snow into its constituent grains, has been measured, as an index of the energy necessary for milling and excavation of snow. The test device consists of a spiked 8-in.-diam drum which disaggregates the snow by plucking grain from grain as a standard cylindrical sample is fed to it. The work done by the drum as it rotates at a speed up to several revolutions per second is given by a record of the torque and the angular travel. The work of disaggregation σ_w, which has the dimensions of stress, is given by:

$$\sigma_w = \frac{T \theta}{V} \qquad (9)$$

where T is the measured torque, θ is the angular travel, and V is the volume of snow disaggregated.

Elastic modulus measurements

Because snow creeps so readily and so rapidly, elastic moduli are often of little significance for design purposes. The practical application of elastic moduli is usually confined to problems involving vibrations or loads which are applied and relaxed very rapidly. Since creep confuses conventional stress/strain records from "static" test procedures and because applications are normally confined to dynamic problems, the elastic moduli for snow are generally determined by dynamic methods.

Measurements may be made *in situ* on large masses of snow by established field seismic methods. The velocities of explosively generated elastic compression and shear waves are measured for specific snow layers, and values of Young's modulus E and Poisson's ratio ν are calculated. Hence the variations of E and ν with depth and snow density can be found. If the velocities of compression (longitudinal) and shear waves are V_p and V_s respectively and ρ is snow density, E and ν are given by:

$$E = \rho V_s^2 \left(\frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2} \right) \tag{10}$$

$$\nu = \frac{1}{2} \left(\frac{V_p^2 - 2V_s^2}{V_p^2 - V_s^2} \right). \tag{11}$$

Laboratory apparatus is available for the determination of Young's modulus by vibration of small beams cut from cohesive snow. A slender bar of snow is cut to shape and vibrated while resting on a pair of supports. Measurement of the resonant frequency gives E, and the rate of damping after the exciting force has been cut off gives a viscosity factor. E is given by:

$$E = \frac{48\,\pi^2 L^4 \rho f^2}{m^4 h^2} \tag{12}$$

where L and h are the length and thickness of the bar respectively, ρ is its bulk density, f is the resonant frequency, and m is a dimensionless constant equal to 4.730 for the fundamental mode. If damping is assumed to follow the Maxwell model, the viscosity factor η_d is given by:

$$\eta_d = \frac{E}{\omega \tan \delta} \tag{13}$$

where ω is the angular frequency and $\tan \delta$ is the loss factor measured by the instrument.

A schematic diagram of the instrument is shown in Figure 16.[17] Small iron plates I_1 and I_2 are frozen to the ends of the bar of snow, which is then laid across two string supports arranged at node points for the fundamental vibration of the bar. A condenser-resistor oscillator is connected to the exciting coil C_1. The oscillating frequency is varied continuously, and at the resonant frequency the current induced in the coil C_2 becomes a maximum. The frequency is recorded. The exciting current is then short-circuited, and the number of vibrations in the time taken for the amplitude to reduce to $\frac{1}{4}$ of its initial value is measured by the three counting tubes D_1, D_2, D_3. The meter M gives the output amplitude, A adjusts the amplitude, and B is the counter control. The calculated loss factor is checked by the electromagnetic oscillograph (EMO).

Young's modulus for dense snow can also be determined from longitudinal vibrations of a long slender specimen, e.g., a core. The modulus E is given by:

$$E = 4\rho L^2 f^2$$

where L is the length of the rod, ρ the snow density, and f the fundamental frequency.
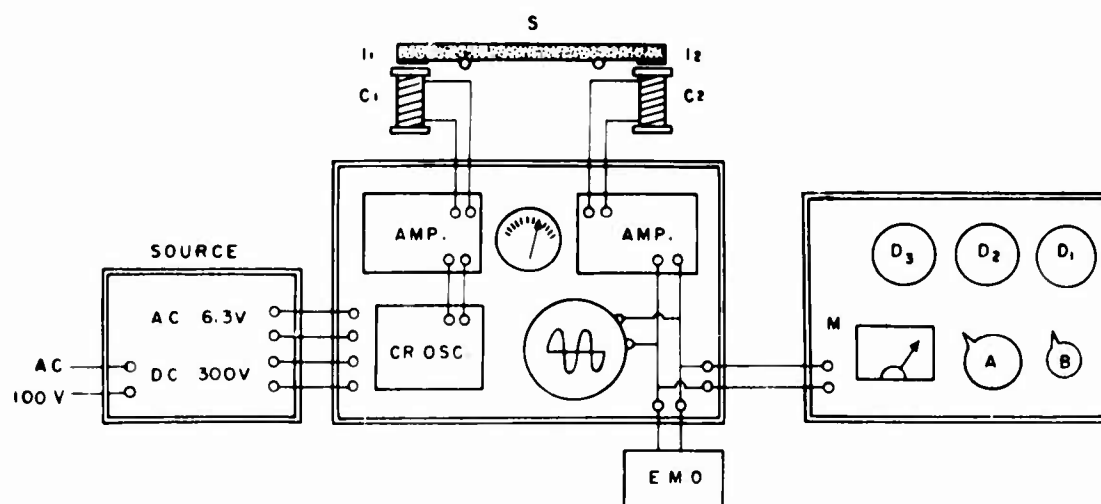
Figure 16. Schematic diagram of the apparatus used for measurement of Young's modulus by flexural vibration (Nakaya[17]).
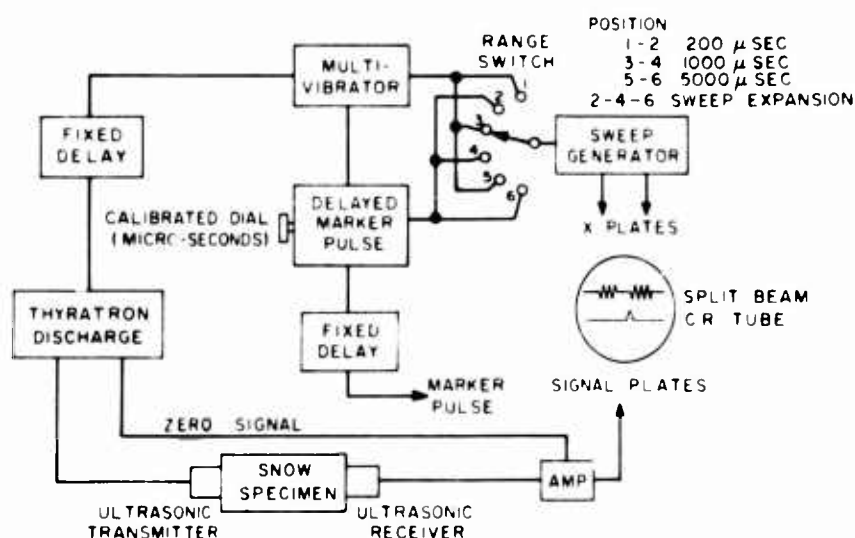
Figure 17. Block diagram of the soniscope, as used for measuring Young's modulus and Poisson's ratio in snow (Smith[21]).

An alternative laboratory method based on the soniscope is probably preferable for general purposes.[23] Brief sonic pulses are transmitted through cylindrical cores (e.g., 3-in. diam) or large blocks (e.g., 1.5-ft cubes) of snow by the soniscope (Fig. 17), and the time taken for the waves to traverse the block to piezoelectric receiver transducers is measured. From the measured wave velocities, E and ν can be calculated in accordance with eq 8, 10, 11.

Laboratory creep tests

The stress condition prevailing in the undisturbed snow of the ice cap is simulated in the laboratory by uniaxial compressive loading when the sample is completely confined laterally. Confined creep tests can be made by loading a cylindrical snow sample axially with a piston while it is confined inside a steel tube. A standard steel sampling tube can be used both to cut the sample and to confine it during the test. For a constant stress test, the piston can be loaded by deadweight through a simple yoke, as shown in Figure 18; higher loads can be provided by lever systems.

*Figure 18. Simple apparatus for multiple confined
compressive creep tests at constant stress.*

The deformation of the sample can be read from a dial micrometer. To avoid adhesion between the
snow and the sides of the confining cylinder, it is desirable to have the cylinder coated with an
inert cryophobic substance, such as Teflon or silicone grease. Laboratory tests permit variation
of stress in order to define the limit of linearity for viscous beh.·vior and to determine the stress
level at which quasi-plastic collapse may occur.

The most common type of creep test is the unconfined compressive test, in which a free-
standing snow cylinder is subjected to a constant axial load, usually by direct deadweight or by
deadweight and a lever system. The deformation is usually read from a dial micrometer which
bears onto the moving load platen. Typical sample sizes range from 1-in. diameter to 2¼-in. diam-
eter. In order to minimize end effects without introducing the danger of buckling, the sample
length is usually about three times the diameter.

In laboratory creep tests, sample deformation is plotted against time to give the creep curve
in the usual way. With relatively low stresses, the creep curve usually displays instantaneous
and delayed elastic response (primary creep) followed by steady secondary creep. With higher
stresses, compressive tests may produce a quasi-plastic collapse of the snow to higher density
in the initial stages; this may be followed by "secondary" creep which decelerates noticeably as
the snow densifies. The most important result from tests is usually the strain rate for secondary
creep (minimum strain rate), which is found by dividing the slope of the creep curve for the sec-
ondary portion by the current length (not the initial length) of the sample. This strain rate is then
related to the stress and temperature of the test and to the density of the snow for the period when
strain rate was measured (i.e., initial density adjusted for the compressive strain which has oc-
curred during testing).

Tensile creep tests are not made very often, but in Switzerland they have been made by
freezing metal plates to the ends of snow cylinders, thus suspending loads from the snow. Verniers,
dial gages, and drum recorders have all been used to measure deformation. The samples were
surrounded by separately suspended glass cylinders to reduce evaporation from the sample.

In any creep tests of long duration it is necessary to take precautions against evaporation
from the specimen. The usual procedure is to saturate the surrounding air with respect to ice by
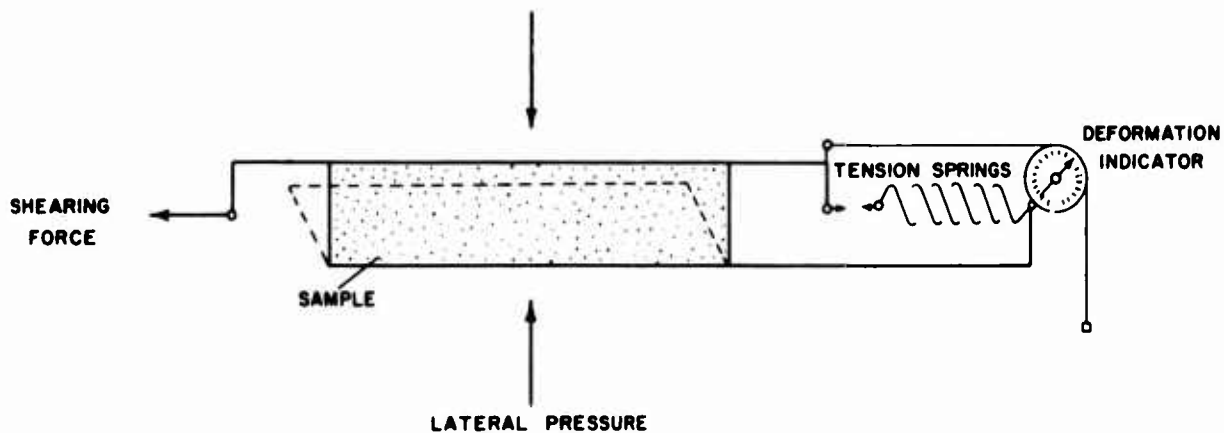
Figure 19. Diagram of an apparatus for making creep tests in direct shear (Haefeli[1]).

piling up snow and periodically stirring it up. The samples themselves may be wrapped very delicately, say with polyethylene sandwich wrap applied loosely.

In uniaxial tests it is usual to measure only one component of stress (axial) and one component of strain rate (also axial). These measurements are insufficient to define the bulk and shear viscosities separately. Attempts have been made to measure lateral strain in unconfined tests and lateral stress in confined tests, but so far there is no way of making these measurements accurately in routine tests. The confined compressive test at low stress gives the viscosity factor defined in eq 14. The unconfined uniaxial test at low stress gives a viscous equivalent of Young's modulus η_E:

$$\eta_E = \frac{9\eta\mu}{3\eta + \mu}. \tag{17}$$

The ratio μ/η, or alternatively the viscous equivalent of Poisson's ratio ν_v, can sometimes be estimated from indirect evidence to a sufficient degree of accuracy. Further details are given in CRSE Monograph III-A3d[14]

Direct shear tests in creep are not often undertaken, but they have been made in Switzerland using an apparatus to which shear forces and lateral forces can be applied simultaneously[5] Shear force is applied to the normally-loaded prismatic snow sample, and after the shear velocity has become approximately steady the movement is retarded by two parallel calibrated tension springs. This gives the shear force corresponding to each velocity of shearing deformation. Figure 19 gives a diagram of the apparatus.

Free water content tests

Determination of the free water content of "warm" snow may be required occasionally.

A common and straightforward method for measuring free water content is the simple calorimetric one. A sample of wet snow is melted in warm water inside a vacuum flask, and the quantity of heat required for melting is found by observing the temperature change in the water contained in the flask. Repeated weighings give the weight of hot water initially in the flask and the weight of the snow. By manipulation of the heat balance equation for the process the following expression for percentage free water content is derived:

$$w = 100 + 1.25 \ t_1 - \frac{1.25}{W_s} (W_w + F)(t_0 - t_1) \qquad (18)$$

where w - percentage free water content

W_s - weight of snow sample (g)

W_w - weight of hot water initially in the calorimeter (g)

F - water equivalent of the calorimeter (cal/$^\circ$C)

t_0 - initial temperature of the hot water ($^\circ$C)

t_1 - final steady temperature of the hot water plus the snow melt water ($^\circ$C).

The heat lost from the calorimeter during introduction of the snow sample is neglected here, so it should be kept to a minimum. A special calorimeter eliminates this problem.[12]

In this method, careful temperature measurement is necessary. A novel variant of the calorimetric method which calls for less precise temperature measurement has been described:[20] in this method the free water of the sample is frozen instead of the snow being melted.

In another approach to the calorimetric method, the snow sample is melted inside a vacuum flask by heating it with an electric current. A special adiabatic calorimeter utilizing this principle has been produced by USA SIPRE.[?]

Calorimetric measurement is inconvenient for rapid field sampling and a number of other principles have been investigated. Since the electrical capacitance of snow varies with the free water content, devices based on the capacitance bridge have been built. Although such instruments show promise in laboratory tests they have not yet proved fully acceptable for field use. Other methods have been based on chemical reactions and on the compressibility characteristics of wet snow.

Thermal properties

The thermal conductivity of snow can usually be determined to the degree of accuracy required for design by referring to existing data. The site material must be classified on the basis of bulk density and grain type, and with this information the thermal conductivity can be determined from data such as are given in CRSE Monograph III-A1.[11] The effective thermal conductivity when air flows through the pores of the snow can be estimated in a similar manner when the permeability of the site material has been measured.

Chemical properties

A chemical analysis of site material may be required sometimes, perhaps to answer water-supply or special water-use questions. In general, polar snow which has not been contaminated by human interference is of very high purity and analyses are likely to be made at laboratories away from the site. The only site problem is to collect snow samples without contaminating them in the process. The simplest method is to cut fairly large samples from freshly revealed snow with clean tools, such as hand saws or coring augers. The samples are transferred to specially cleaned containers with a minimum of handling, and if possible transported to the test laboratory without melting. There, the outer layers of snow, which have been contaminated to some extent, can be stripped away under clean conditions and the remaining snow is available for test.

Dielectric and optical properties

Although the measurement of dielectric and optical properties is not normally considered to be a part of construction site investigation, there may be a call for such data during design of a complex ice-cap facility. There are no standard techniques for routine testing, but it is likely that requirements for design data can be met in most instances from existing data compilations when the index properties of density, temperature and grain type have been measured on site. Relevant data are given in CRSE Monograph III-A1.

Relevant Material Properties

Most surface snow is relatively soft and easy to excavate. Dense dry snow typical of polar snowfields has excavating characteristics roughly comparable with those of a dry silt: it can be dug easily and breaks into large clean-cut blocks and cohesionless fine fragments. By contrast, wet snow has a tendency to form cohesive clods and clumps during excavation. The deposits of dry snow which cover much of Greenland and Antarctica exhibit a high degree of uniformity in mechanical properties; in lateral directions there is virtually no variation in properties for great distances, while the snow gradually increases in bulk density and strength with increasing depth below the surface. In areas which are subject to summer melting the snow properties are broadly similar to those of dry snow, but hard ice bands and discontinuous ice lenses are interspersed between the layers of relatively soft snow.

The bulk density, or unit weight, of snow ranges from less than 0.1 g/cm^3 (< 6 lb/ft^3) to about 0.8 g/cm^3 (50 lb/ft^3); when density exceeds 0.8 g/cm^3 the material is impermeable, and by convention is termed *ice*. Unless the snow has been freshly deposited or recently disturbed, bulk density provides a good index of strength properties: the shear strength* under low confining stress ranges from about 10^{-3} kgf/cm^2 (~ 0.014 lbf/in^2) at the lowest densities to more than 10 kgf/cm^2 (> 140 lbf/in^2) at high snow densities. Strength varies also with temperature and grain type, but for excavating considerations these effects are relatively insignificant compared with density-dependence.

A measure of the work required to cut or break snow is given by the "energy of disaggregation," i.e., the energy required to separate unit volume of the snow into its constituent grains or into fragments of grain size. With special apparatus, the energy of disaggregation can be measured directly, but it can be shown that for many practical purposes an adequate indication of the energy of disaggregation is given by the unconfined compressive strength under conditions of brittle fracture. Dimensionally, energy of disaggregation has the units of stress (e.g., in.-lbf/in^3 = lbf/in^2). Unconfined compressive strength ranges from about 0.01 kgf/cm^2 (0.14 lbf/in^2) in low-density (≈ 0.1 g/cm^3) snow to about 100 kgf/cm^2 (1400 lbf/in.^{2}) in very dense (> 0.7 g/cm^3) snow.

The enormous overall variation of strength for snow necessitates a variety of material-handling techniques. At the lower end of the scale, light fluffy snow has no significant strength and it is handled somewhat like a fluid, e.g., in snow removal from roads and airfields. At the upper end of the scale, where snow is much like bubbly ice, the material has to be cut or broken in the same way as a soft rock.

Most snow has sufficient cohesion, or tensile strength, to stand unsupported in vertical cuts and boreholes. Because the bulk density, and hence the strength, increases with increasing overburden pressure, very deep cuts and holes stand unsupported for a limited amount of time. Natural snow cliffs at the edge of Antarctic ice shelves, together with crevasse walls, indicate that cuts up to 150 ft deep can stand vertically. However, such cuts deform by visco-plastic flow. In the same way, tunnels may be cut into natural snow deposits at any depth without danger of sudden collapse, although they gradually deform and close as the snow creeps under gravity body forces.

The peculiar bonding properties of snow are worthy of special note in connection with excavation. Even at low temperatures, fine particles of snow (~ 0.1-mm grain size) adhere to each other on contact. The initial adhesion is weak, but with the passage of time ice bonds grow between the adhering particles by the process of molecular diffusion known as sintering or "age-hardening." Thus the strength of a freshly deposited mass of fine-grained snow increases exponentially with time, the rate of increase depending chiefly on temperature. One practical result of

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*Strength varies appreciably with loading rate or strain rate; here the concern is with moderately high loading rates which produce brittle rather than ductile failure.

this process is that fresh snowdrifts, or deposits from rotary snowplows, are transformed quite rapidly from weak and almost cohesionless material to hard cohesive masses. Another result is that very finely comminuted particles adhere so readily that cutting and blowing equipment can be coated and clogged very rapidly; in particular, it is difficult to transport comminuted snow pneumatically.

In drilling into, or through, snow deposits the permeability of the material has to be taken into consideration, since drilling fluids cannot be retained in a hole unless casing is placed. Permeability decreases with decreasing porosity, or increasing density, becoming virtually zero at a bulk density of approximately 0.8 g/cm³ (50 lb/ft³).

Excavating Methods and Equipment

Because snow is a relatively weak material, most excavating techniques are quite conventional. Disengagement of the material presents no great problem, and the limit on speed of excavation is usually set by the capacity for transporting spoil to the disposal area. Melting is sometimes suggested as an alternative to mechanical handling, but a simple consideration of energy requirements shows that in most cases mechanical handling is vastly more economical than melting.

Hand digging

With the very high cost of labor in remote polar regions, hand digging is employed only where small quantities of material have to be moved. It can be used for making exploratory pits and trenches of small dimensions, narrow shafts and small bore tunnels; it can also be used for recovering fragile stores and equipment which have been buried by snow. Hand labor is also used for maintenance cutting in undersnow installations which have suffered severe deformation.

Near the surface, snow is generally soft enough to be dug directly with spades and shovels, but dense hard snow below the surface usually has to be broken with a pick or an adze before shovelling. Hard snow can be cut out in blocks using handsaws or powered chain saws. Chain saws are probably the most satisfactory handtools for excavation of very hard snow, particularly in small shafts and tunnels where space is restricted.

The spoil from hand excavation can be handled by intermittent batch disposal. Tunnels or trenches can be mucked out with high-sided sledges running to a dumping frame, and spoil from pits and shafts can be hauled out in winch-wound buckets.

Blading

Crawler tractors have a wide range of uses on polar snowfields (freight hauling, blading, lifting, winching and power takeoff), so bulldozers are often used for excavating because of their economic suitability for the overall project. Conventional methods of operation are used for cutting and filling, but at remote sites bulldozers are occasionally used for jobs which might be done more effectively by other types of equipment - if that equipment was available.

Bulldozers are used to cut trenches, excavate for foundations, place fills for runways or backfills over foundations, and remove unwanted snowdrifts (Fig. 20). Wide tracks (but not full low-ground-pressure conversions) are desirable, and full winterization of machines is a necessity. Turboblowers are advantageous at high altitudes. Front-end loaders on tractors are also used for general digging and for special jobs, such as filling the hoppers of snow-melting tanks.

Large excavations were made with bulldozers at DYE 2 and DYE 3 (ice-cap radar stations in southern Greenland), where snow was taken out to a depth of 30 ft to permit placing of foundations and POL (petroleum-oil-lubricant) tanks (Fig. 21). Snow was pushed up ramps at the end of the excavation and bladed away from the lip of the hole. The bulldozers later backfilled the holes and compacted the fill in layers.
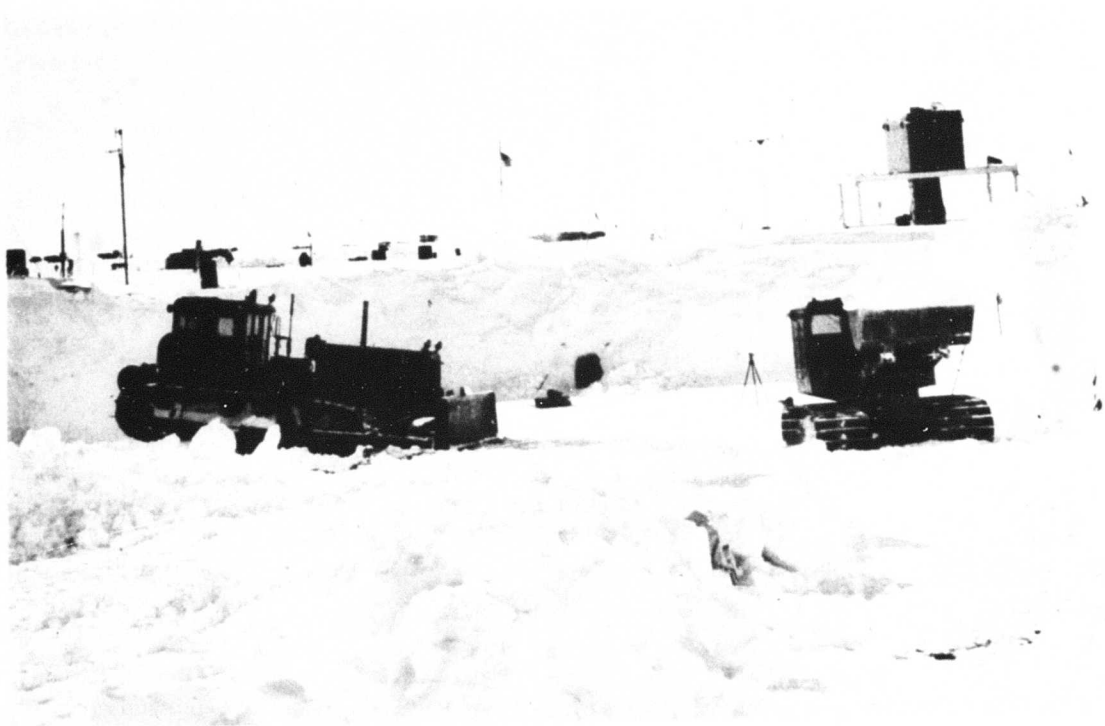
Figure 20. General excavation. Bulldozer and front-end loader excavating a building site at Byrd Station, Antarctica. (Official U.S. Navy photo.)

Figure 21. Bulldozers excavating a large pit at DYE-2, Greenland. The snow at this site contains heavy ice lenses. (Photo by J. McAnerney.)

Shovels, draglines and clamshells

Power shovels, draglines (Fig. 22) and clamshells (Fig. 23) are used in the normal way when digging snow. Modifications to the machines are not usually necessary, although a machine can dig above its rated capacity if a lightweight bucket (e.g., an underwater bucket) is fitted. The ground pressures of standard crawler shovels are rather high for travel on virgin snow, but they are perfectly acceptable for most construction operations. Some sites have snow which is (or becomes) firm enough for wheeled cranes and shovels to be operated. Power shovels can be used for stripping surface snow, deep excavating, ditching, banking, fill-spreading, drift removal and loading onto muck-hauling sleds.

The expense of transporting a power shovel to a remote site in Greenland or Antarctica is considerable, particularly if air transport is required at any stage of the journey, and use of a power shovel is therefore economical only if there is plenty of work for which this type of machine is specially suited. A dragline might perhaps be justified if it doubled as a crane for other phases of construction.

Trenching machines

Trenching machines have not been used in snow to any extent so far, but they might be useful on some special jobs. Both boom trenchers and bucket-wheel trenchers should operate satisfactorily without much modification, although low-ground-pressure tracks might improve performance. These machines are capable of cutting trenches up to about 5 ft wide and up to 16 ft deep; they might possibly be used for laying pipelines and making small storage and communication trenches at under-snow installations. They have been useful in cutting drainage trenches in connection with experimental road construction on an ice ramp covered with winter snow.

Large-diameter augers

Large-diameter earth-boring machines (Fig. 24) can be used for digging vertical, and inclined, shafts with great rapidity. Commercially available augers can dig holes to depths of about 125 ft with diameters up to 8 ft, but special machines can be built for digging larger-diameter holes in snow to depths of 250 ft. Depth is limited by the length of the kelly, but extending telescopic kelly bars could overcome this limitation.

Commercially available bucket auger crane attachments offer good possibilities for sinking shafts in snow. Standard models dig holes up to 10 ft in diameter and up to 200 ft deep.

A short helical auger is raised each time the helix fills with snow, and the snow is thrown clear at the top of the hole by spinning the auger; a bucket auger is raised each time the bucket fills and a turntable is required for dumping.

Shafts can also be dug using orange-peel-type buckets and Benoto tools dropped and hoisted from sheer legs.

Rotary snowplows

The only unconventional excavating machine used in snow is the rotary snowplow, which has proved to be efficient for rapid excavation and precise cutting. Rotary plows have a special advantage in that the finely milled cuttings ejected from the machines form a rapid-hardening aggregate of very strong snow, which can be used to form pavements or structural elements.

The principal machine which has been used operationally by the U.S. Army and the U.S. Navy is the Peter Snowmiller, a Swiss plow. It has been used to cut the trenches for under-snow installations at Camp Fistclench and Camp Century in Greenland, and at Byrd Station in Antarctica.
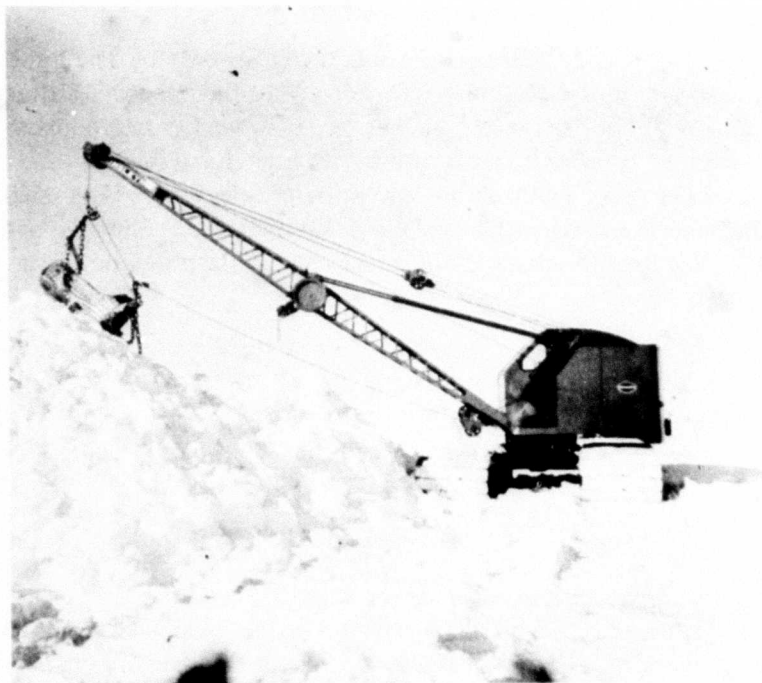
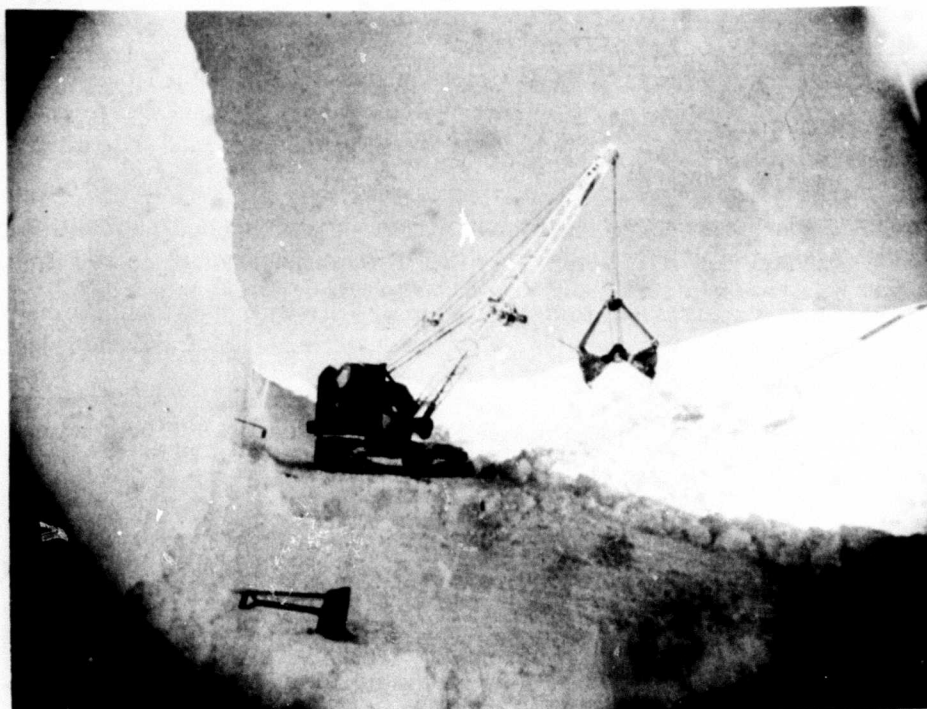Figure 22. Wide-track machine working as a dragline on the Green-land Ice Cap.

Figure 23. Wide-track machine using a clam bucket on the Greenland Ice Cap.
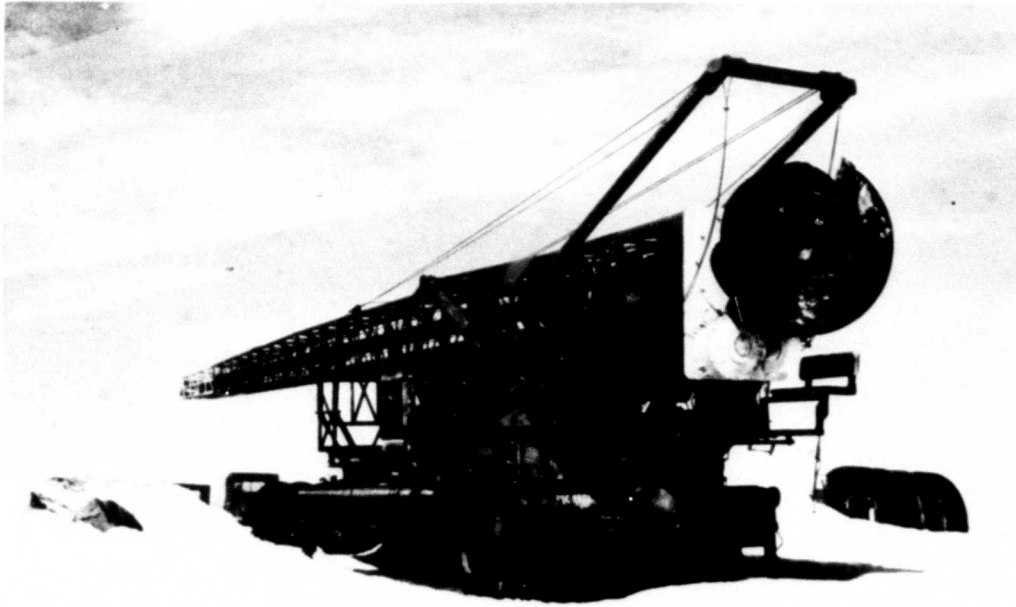
Figure 24. Large-diameter auger – Williams Hole Digger Type LDH 70.

The Peter Snowmiller is a crawler machine fitted with helical blades which rotate about a transverse horizontal axis. The whirling blades mill lying snow to a fine grain size and the machine then blasts a stream of snow particles out through an ejection chute. Various types of ejection chutes can be fitted, from stub chutes for long flat throws to tall chutes for high lifts from a trench. The maximum casting height is about 27 ft. The normal maximum output of the machine is from 200 to 500 tons/hr in surface polar snow*; the output varies with travel speed and with the density and hardness of the snow in place. The forward cutting speed is about 8 to 16 ft/min. For subsurface cutting the machine averages about 150 tons/hr. Figure 25 shows a Peter Snowmiller making an undercut trench on the Greenland Ice Cap. The standard Peter Snowmiller is shown in Figure 26 and outline specifications for one model are given below.

Peter Snowmiller (Type DHR 1-230)

Weight: 36,000 lb

Length: 24 ft 11 in.

Working width: 8 ft 10 in.

Height: 11 ft

Distance between tracks ("track"): 5 ft 7 in. centers

Power plant: GM 2-stroke 6-cylinder diesel developing 230 bhp at 1,800 rpm

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*At an altitude of 7,000 ft above sea level. All internal combustion engines lose power at high altitude, and sites on polar snowfields are commonly at 6,000 to 10,000-ft elevations.
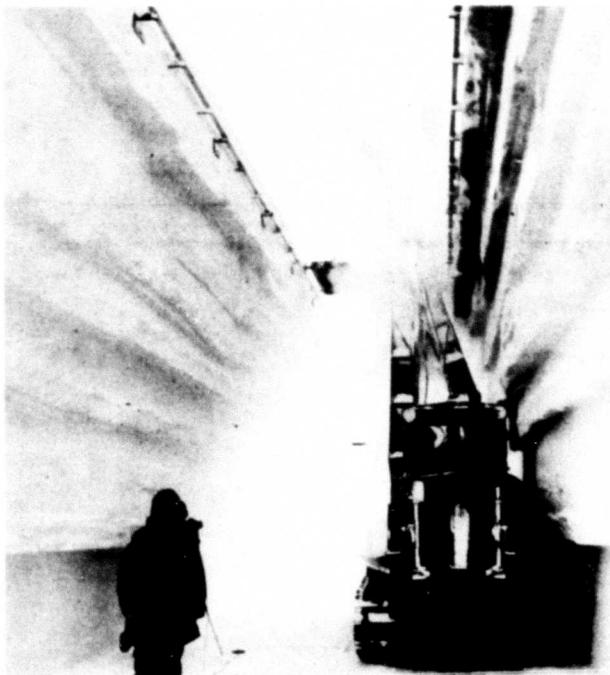
Figure 25. Peter Snowmiller with medium-height casting chute making an undercut trench on the Greenland Ice Cap. The rails near the lip of the trench carry a guide trolley for the miller.
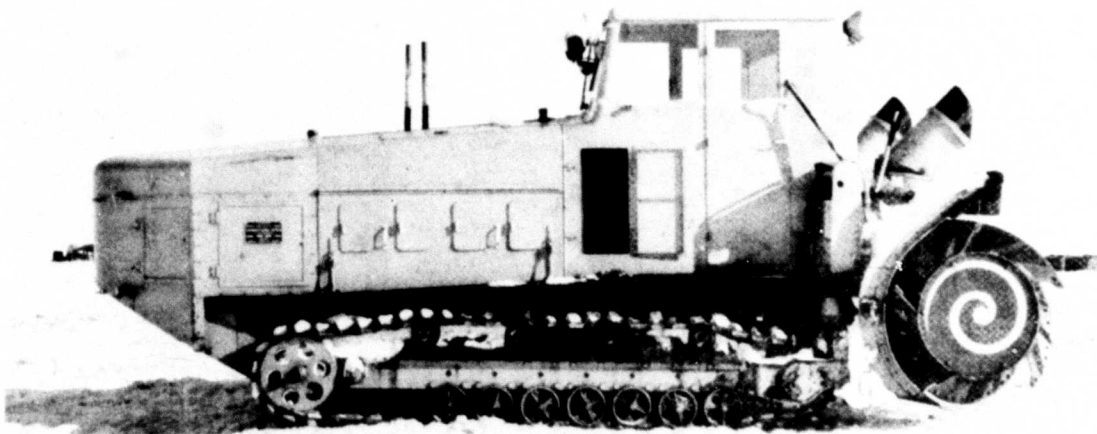
Figure 26. Peter Snowmiller – standard configuration.

Transmission: Engine drives main shaft through main transmission; each track is driven by a multipiston hydraulic motor fed by multipiston pumps running off the main shaft; miller drum drives off the main shaft through a longitudinal shaft, a three-speed gear, and bevel gearing.

Fuel capacity: 119 gal

Manufacturer: Konrad Peter Aktiengesellschaft, Liestal, Switzerland

Traveling speed: 7 mph

Working speed: 0 - 2.5 mph

Ground contact pressure: 7.1 psi

Turning radius: 50 ft

Maximum casting height: 27 ft

Maximum casting distance (no wind): 50 - 60 ft

Output: 200 - 500 ton/hr in polar snow

Fuel consumption: 11.7 gal/hr

Drum speeds: 225 and 305 rpm

Drum diameter: 4 ft (to cutting edges)

For small-scale operations, hand-maneuvered rotary plows can be used. These range in size from heavy self-propelled crawler types such as the Swiss Peter Junior (Fig. 27) down to tiny machines of the domestic snow-blower variety.
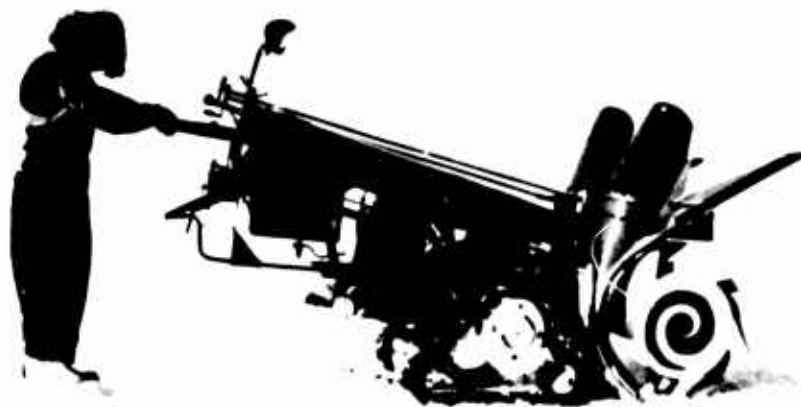
Figure 27. Peter Junior rotary plow.

Scrapers

Scrapers have rarely been used for moving ice-cap snow up to the present time. Standard scrapers, however, operate without significant modification in the ice-cap environment and are used regularly for leveling snow drifts at the DYE sites in southern Greenland.

Special machines

Since all types of snow are easy to break and disengage it is a straightforward engineering problem to design special-purpose cutting machines. Such machines have been devised for tunneling and for maintenance cutting in tunnels. The real problem lies in the design of conveyor systems which can keep pace with the continuous cutting elements.

Melting

While the melting of large quantities of snow purely for excavation purposes is unfeasible, large undersnow cavities can be made as a byproduct of water production. The cavities left after large-scale *in-situ* snow-melting operations might be used for POL storage, or for other purposes which can be satisfied by a cavity of irregular form. Details of *in-situ* snow melting are given in another section.

Blasting

Rarely is any advantage gained from blasting in snow. Because snow is so effective in attenuating shock waves, blasting is relatively inefficient. Furthermore, blasting usually does nothing to solve the problem of spoil removal, which is often a greater problem than cutting.

One situation in which explosives might be profitably employed is at the edge of an Antarctic ice shelf, where cliffs of dense snow drop almost vertically to the sea. Should any ramping of these cliffs be required, say to provide vehicle access to the sea ice or to provide port facilities for ships, blasting might be useful. A procedure for designing such a blasting operation is outlined in CRSE Monograph III-A3a.[1] A detailed discussion of the effects of explosives on snow is given in that monograph, which lists data for the dimensions of craters formed in typical types of snow by high explosives.

Special excavations

In addition to common surface excavations, special types of excavation have been required repeatedly at ice-cap sites over the past decade. These include large trenches for production of tunnels by the cut-and-cover method, pure tunnels and narrow shafts.

Trenching

The only extensive trenching on polar snowfields so far has been accomplished with the aid of Peter Snowmillers. There are several reasons behind the preference for these machines: bulldozers are inefficient for deep trenching because of the difficulty of clearing spoil to the surface from a long cut, draglines are unable to undercut and lack cutting precision, trenching machines suffer from size limitations, and finally the snow comminuted by a Peter plow can be used as a construction aggregate.

Figure 28a shows a cutting sequence for a trench 21 ft 4 in. deep and 8 ft 10 in. wide. This is a trench with vertical walls, and width equal to the width of a Peter miller cutter. Density and hardness of the snow increase with depth; consequently the output of the machine decreases with depth. With the first pass of the machine in this case, the cut depth is 4 ft, which is equal to the full diameter of the milling drum. On the second pass a 3-ft 7-in.-deep cut is made, and on the third pass the cutting depth is reduced to 2 ft.
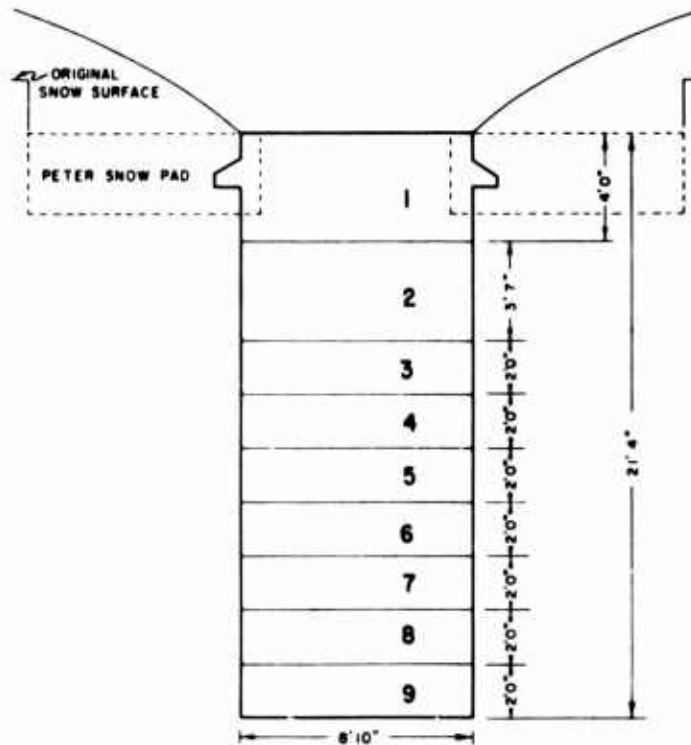
a. Narrow vertical-wall trench.
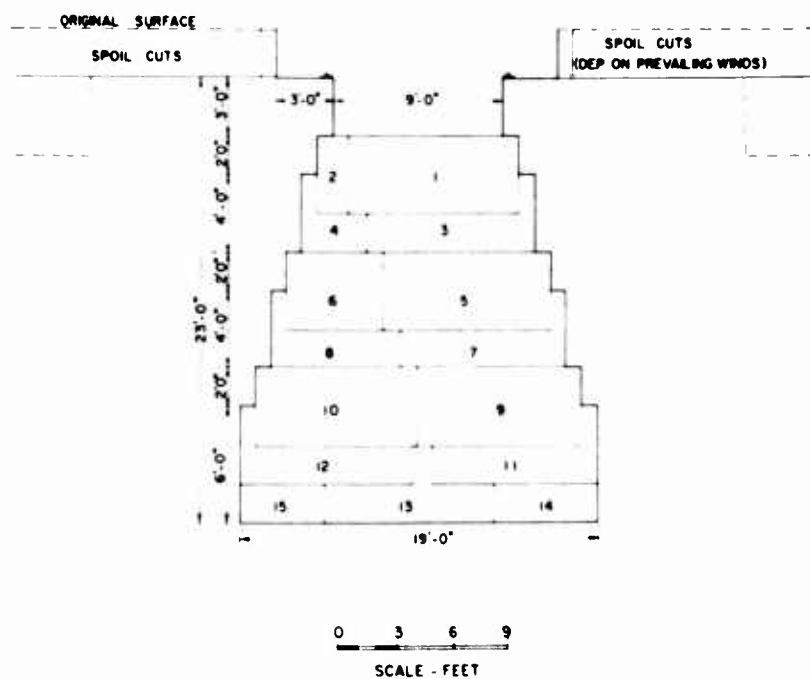
b. 9-ft undercut trench as designed for Camp Century.

Figure 28. Examples of cutting schedules for trench excavation by
Peter Snowmillers. (Schedules a and b proposed by R.W. Waterhouse.)
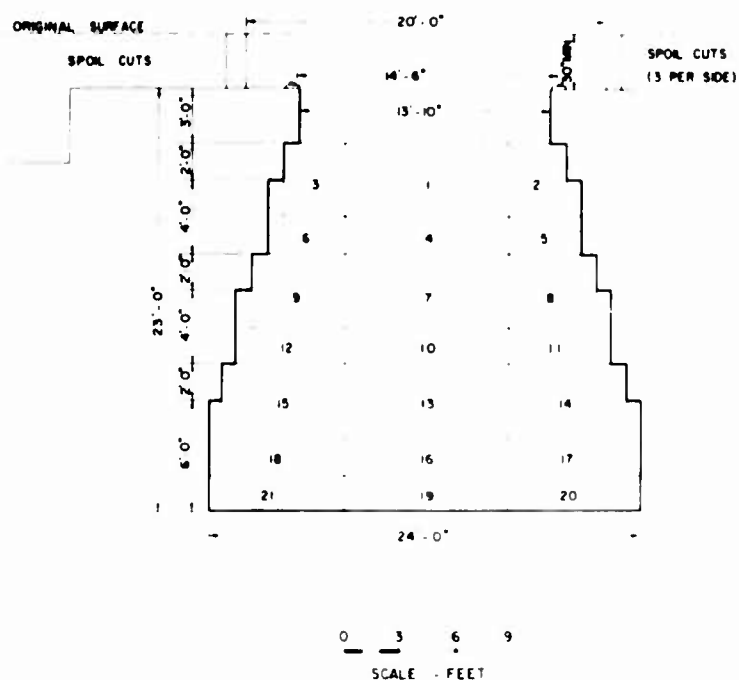
c. 14-ft undercut trench as designed for Camp Century.
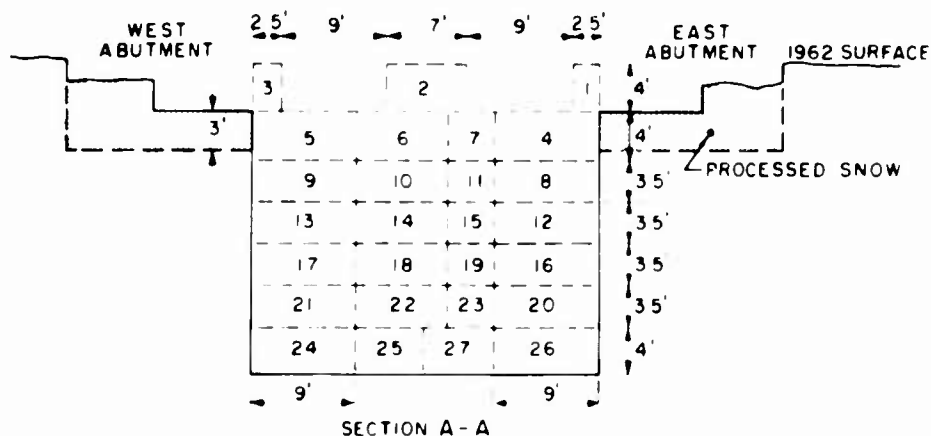
d. 30-ft-wide straight-wall trench.

Figure 28 (Cont'd). Examples of cutting schedules for trench excavation by Peter Snowmillers. (Schedule c proposed by R.W. Waterhouse; schedule d from Tobiasson and Rissling.[27])

When the miller is working close to the surface it is fitted with short casting chutes, and the milled snow is blown well clear of the trench on the downwind side. At somewhat greater depths the medium-height ejection chute can be used, and when the machine is working near its maximum depth (about 25 ft) the high ejection chute is used to clear cuttings over the lip of the trench.

Figure 28c gives a cutting sequence for a trench 23 ft deep, 13 ft 10 in. wide at the top, and undercut in steps to a width of 24 ft at floor level. The maximum width of undercut which can be made in one step with the Peter miller is 10 in.

Figure 28d shows a cutting sequence for a 30-ft-wide straight-wall trench. Detailed production data for this cutting operation are given in reference 27.

Figure 29 gives a set of cutting sequences for another trench construction project in Greenland. Detailed production analyses for this job are given in reference 1. During trench cutting the miller output averaged 359 yd^3/hr, or 134 ton/hr. The overall output, including surface spoil cuts, averaged 466 yd^3/hr, or 166 ton/hr.

Figure 30 gives data from Peter miller performance tests which were made on the Greenland Ice Cap. They illustrate the decrease in output with increase of working depth and reflect the increase of strength and density of snow with increasing depth. In Figure 31 the output of a Peter miller is related to forward cutting speed and snow density.

Visibility is something of a problem when a Peter miller is operating, and attempts have been made to develop a guide sled to carry adjustable targets for miller drivers. However, a more flexible procedure is to have a survey crew running string lines, which the miller driver follows with a pointer attached to the side of his cab.

Trenches cut in polar snowfields, where the density of the top few feet of snow is about 0.4, do not require timbering or wall support of any kind for stability. Closure occurs over a period of years, but it takes place by a process of slow viscous deformation. Vertical compression, or densification, of the surrounding snow causes a relatively rapid reduction in the vertical dimensions of a trench.

Figure 29. Cutting sequences employed during a trench construction project in Greenland. The initial surface cuts are spoil cuts (Abele[1]).

END VIEW

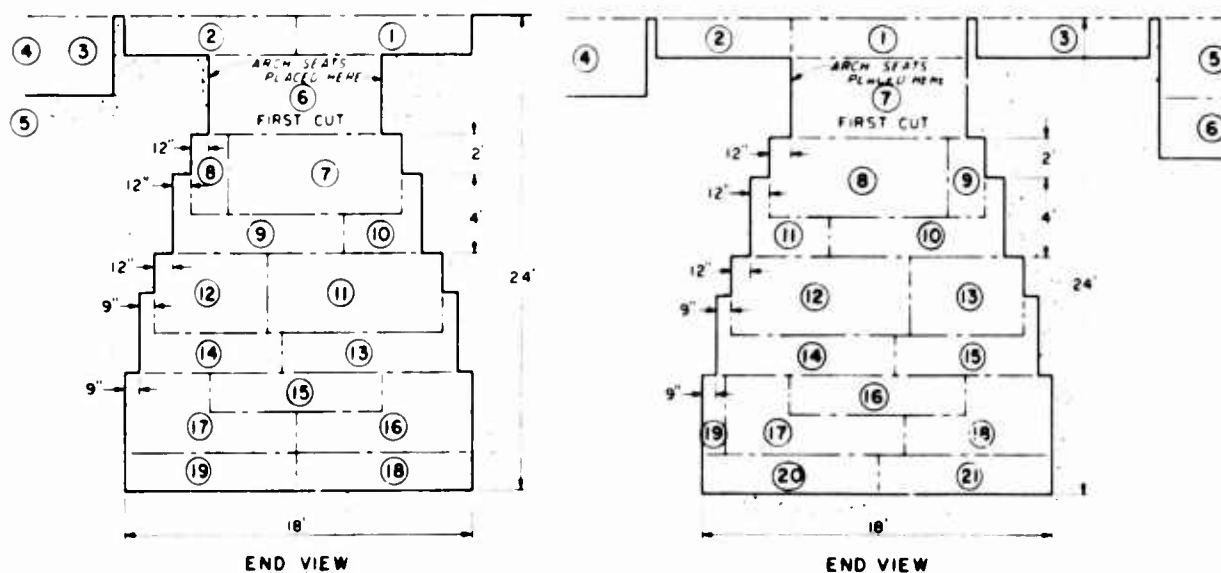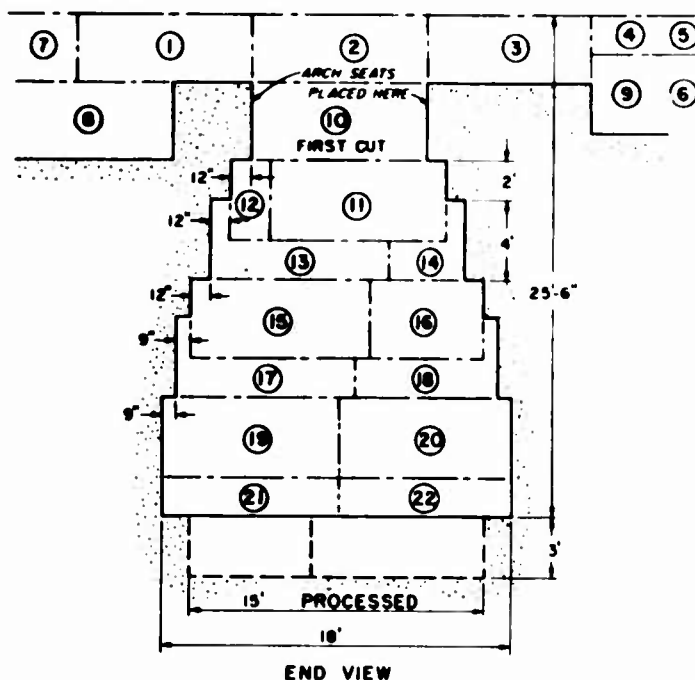*Figure 29 (Cont'd). Cutting sequences employed during a trench construction project in Greenland. The initial surface cuts are spoil cuts (Abele[1]).*
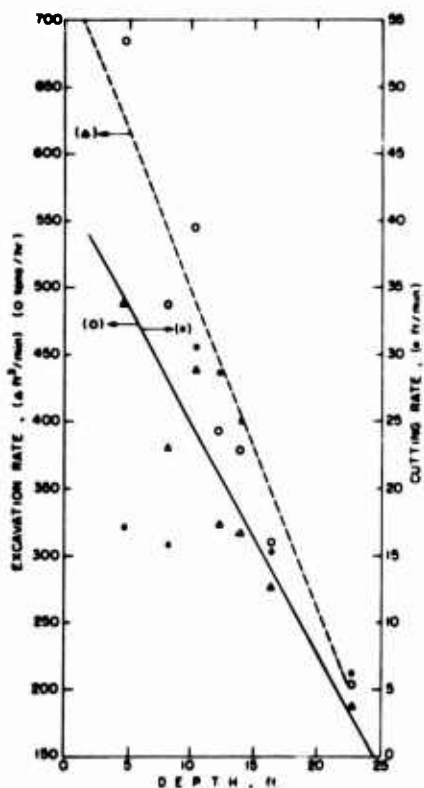

Figure 30. Excavation rate vs depth below the snow surface for a Peter miller working at 7000 ft a.s.l. on the Greenland Ice Cap. (Data from tests by Minsk[11]).
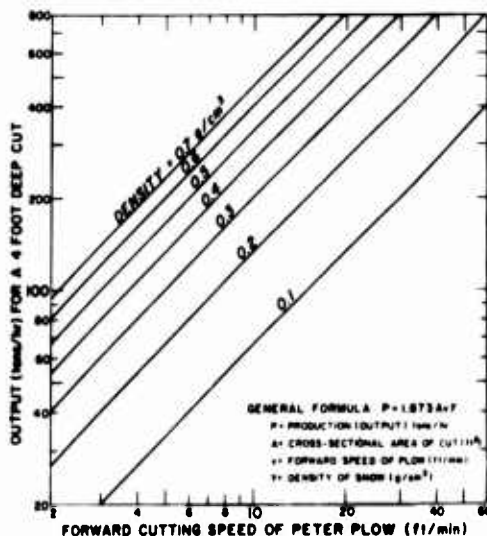

Figure 31. Reference chart relating Peter Snowmiller output to forward cutting speed and snow density (Abele[1]).

Tunneling

Early experimental tunnels excavated in the snow of the Greenland Ice Cap were dug by hand. At shallow depths shovels, picks and adzes were used, but in the deep hard snow it was necessary to use saws and adz-like tools at the working face. The tunnels were trimmed to a circular cross section with a rotating beam cutter. Spoil was cleared from the working on high-sided sleds, which were winch-hauled to the portal for dumping. In later tunnels and inclined drifts, snow was cut by chain saws and cleared by conveyors.

For tunneling in dense hard ice, coal saws and continuous mining machinery have been used with success, but these machines are unnecessarily powerful and heavy for tunneling in friable snow. Following the success of rotary snow plows in cutting hard snow, a special machine for tunneling in snow, the Russell miner, was designed at USA CRREL. This consisted basically of a rapidly rotating drum armed with cutting teeth and a swinging arm mount for the drum. Being an experimental machine, its performance left much to be desired; the best recorded performance of the machine was an advance of only 22 ft in 24 hr in a 9-ft × 9-ft drift.

In association with the Russell miner a special pneumatic conveyor was built. This consisted of 12-in.-diam pipe with fan stations set at 200-ft intervals to provide the required airflow. The fans were 25-hp axial-flow types. Each fan, including its electric motor, was mounted inside the conveyor conduit. This miner-conveyor system was unsatisfactory because particles produced by the cutter head were too small; the in-line fans further disaggregated the snow particles and heated the air/snow mixture. The result was snow deposition, mainly near the fans, and blockage of the conveyor system. While the problems of the system undoubtedly were aggravated by the presence in the line of fan blades and motors it does appear that there may be serious difficulties in carrying very finely-comminuted particles by turbulent diffusion because the high surface free energy of snow particles less than 100μ in size causes ready adhesion.

In tests to improve the performance of the Russell miner the cutter-head was modified to produce larger (2 mm) particles and the fans were grouped in line at the delivery end of the conveyor pipe. In the initial tests, cutting rates of 6 ft/hr were obtained in an 8 ft by 7 ft drift.

With these modifications there is little doubt that an efficient tunneling system could be developed based on the original principles but time did not permit such development for the use of the improved system in excavating the "Inclined Drift."

The most extensive pure tunnel to be cut in polar snow was the "Inclined Drift" at Camp Century (Fig. 32). This consisted of a main tunnel, inclined at approximately 20° to the horizontal, which penetrated to a depth of 100 m (330 ft) below the ice-cap surface. Down to a depth of 127 ft (482 ft along the incline) the tunnel had a 9-ft × 9-ft cross section, and below this level pinched down to 6 ft × 6 ft. At the bottom, two horizontal tunnels, each 6 ft × 6 ft in cross section, ran 100 m (330 ft) out in the north-south and east-west directions. Excavation began with the Russell Miner System which was soon abandoned in favor of hand-held chain saws (Fig. 33) and a screw-conveyor. The conveyor worked well but had to be fed by hand because its helical collection device was unsatisfactory; hand-feeding was also hazardous to personnel.

Tunnels in polar snow do not require shoring; sudden collapse is highly improbable and closure occurs by slow visco-plastic deformation. If tunnel walls are to be restrained for any reason, complete sheeting is necessary, since snow flows around discontinuous supporting members.

As depth below the surface increases, the weight of overburden, and consequently the intensity of stress around a tunnel, also increases. However, there is a corresponding increase of snow density with depth, and observations on excavations and boreholes indicate that there may be an optimum depth at which closure rate is a minimum. In the interior of northern Greenland this optimum depth seems to be between 60 and 120 ft below the surface.

Figure 32.   The "Inclined Drift" at Camp Century, Greenland.

Figure 33.   Chain saw being used to cut hard snow in a Greenland tunneling operation.

Digging shafts

Most of the shafts dug on polar snowfields so far have been for exploratory or scientific purposes, and hand digging with pick, shovels and chain saws has been employed. Maximum depths have been around 150 ft, and the shafts have sometimes been inclined at about 15° from the vertical to facilitate access, which is provided by ladders pegged into a 75° wall, with stages at 15-ft intervals. Spoil has been lifted out in buckets hauled to the surface by winch or by a tractor running back and forth.

An orange-peel type of drop-tool (Benoto tool) has been used to excavate 3-ft-diam shafts to a depth of 100 ft in Greenland. When the tool was hauled to the surface after each grab, a dumping sled was run across the top of the hole and the spoil dropped directly onto it.

Shafts up to 8 ft in diameter and up to 150 ft in depth can be excavated rapidly with large augers but, since such augering rigs are heavy and expensive, their use at remote polar sites would be justifiable only if many shafts were required.

A more promising item is the bucket auger crane attachment, which digs 1 - 10-ft-diam holes to 150 ft using a telescopic kelly. It can be mounted rapidly onto a normal ¾ ton crawler crane.

If wide shafts have to be excavated, the work can probably be accomplished most effectively with clamshells.

Ice-cap water wells have been sunk with steam points, and steaming or hotpoint boring might be worth consideration for certain types of shafts.

As with other types of snow excavations, the walls of a shaft do not collapse suddenly, and width can be maintained by periodic wall-cutting instead of placing retaining structures. If a shaft has to be lined, however, consolidation of the surrounding snow must be taken into consideration. If a rigid shaft lining is installed in contact with the surrounding snow, downward shear forces may be transmitted to the rigid lining as the snow beside it compresses vertically under the weight of new snow at the surface. For this reason shaft walls should be designed so that shear is not transmitted from the snow to the main structure.

Drilling

Since all snow is relatively easy to cut, the chief problem in designing suitable mechanical drilling equipment is the clearance of cuttings. Snow is permeable, so drilling fluids cannot be circulated unless the hole is cased.

For drilling to shallow depths, augers are the most convenient tools. A standard item is the USA CRREL 3-in. coring auger; it consists of a 1-m-long core barrel wrapped with external auger flights, and extension rod made up in 1-m lengths. The auger is turned by hand using either a bit brace or a T-bar. The extensions are joined by an external sleeve, with a rapid-coupling pin securing the connection. The cutting head is fitted with two chisel-type tools, which can be removed for sharpening. In the standard form for hand operation, the 3-in. coring auger can penetrate to a practical maximum of about 15 m (50 ft); the only items needed in addition to those in the standard kit are a cover board for the hole and some type of fork or split collet to hold the drill string while coupling is in progress. If a hoisting tripod is used, it becomes feasible to core about 30 m (100 ft); a small motor attachment for turning the drill is then desirable,* although there is a danger of jamming the auger if power is applied carelessly.

If there is no requirement for continuous core, power flight augers can be used. Standard commercial equipment for shallow drilling in soft formations can be used; this equipment can be sled-mounted or attached directly to oversnow vehicles. Bits should be designed to cut ice layers which may occur. Intermittent cores can be taken with the barrel of a USA CRREL auger, or with a similar barrel, providing the main auger drills a hole large enough to admit the core barrel.

As was mentioned earlier (p. 27) very large-diameter augers should have no difficulty in boring large holes or shafts in any type of snow.

The practical limit of drilling depth for small-diameter augers in snow seems to be about 40 m (130 ft). Below 30 m (100 ft), progress becomes extremely slow, as the auger is unable to clear its cuttings. Because the hole walls are soft, the hole becomes enlarged by "thrashing" of the drill string, and cuttings simply spill off the flights. With any auger, care must be exercised to avoid jamming. If the drill is allowed to penetrate too fast, cuttings may jam the flights, and even though snow is relatively soft it grips the string tightly enough to cause a twist-off.

The Arctic Construction and Frost Effects Laboratory (ACFEL) was responsible for the development of the CRREL coring auger. Reference may be made to ACFEL Technical Reports 15, 22, 25, 46 and 50 for further details.

When core is not required, it may be more convenient to use a hotpoint than an auger. A variety of electrical hotpoint borers have been developed for use in snow and ice, and the simple types which are adequate for drilling to shallow depths in snow are both cheap to build and easy to use. As long as the hotpoint borer is operating in permeable snow, nothing more than a melting head is required; the melt water simply soaks into the surrounding snow and leaves a dry hole. A small hole can be drilled quite rapidly with only half a kilowatt of power. The limit of depth for this type of hotpoint is set by the reduction of snow permeability with depth in "cold" (subfreezing)

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*At Ice Island T-3, a hand-operated 3-in. coring auger was used to measure the ice thickness, 107 ft, with only the help of a simple tripod to support the auger rods.

snow; when water begins to pond in the hole it freezes back above the hotpoint. On the Greenland and Antarctic ice caps, snow permeability reduces to zero at about 40-m (130-ft) depth at fairly warm sites, and at about 150-m (500-ft) depth at the coldest sites. In "warm" (0C) snow and ice there is no limit in principle to the depth of penetration for a simple self-plumbing hotpoint; the hole just remains water-filled.

For thermal coring in snow and ice, including deep coring in "cold" ice, special equipment has been developed by USA CRREL. Basically it consists of an annular electric heater, a core barrel, and a heated storage chamber for melt water sucked away from the main heating element. The drilling unit is lowered and raised by its power supply cable, so that core can be pulled much faster than would be the case with conventional rotary equipment. One special use for this equipment is penetration of the permeable upper layers for the first stage of deep drilling in an ice cap. When the hole has been drilled to a few hundred feet by the thermal coring drill, casing can be placed, the hole can be filled with fluid, and a downhole electromechanical drill can take over for the deeper drilling. Current models of the thermal coring drill have power demands of 2½ to 3 kw.

More detailed descriptions of equipment and techniques for drilling snow and ice will be given elsewhere in this series.

Introduction

Snow is the only material which occurs locally over most of the area of Greenland and Antarctica. It has to be used as a foundation material and as a medium for embedment, and it must be considered for use as a structural material. While it is undeniable that snow has mechanical properties that are difficult to deal with, the snow found in polar snowfields is a good deal stronger than the familiar seasonal snow of the temperate regions; typical polar snow is a firm and competent material which can stand unsupported in excavations and which can be cut into blocks and handled.

A number of dominant features of the mechanical behavior of snow have to be kept in mind when it is considered as a structural material. While snow may behave elastically and display appreciable strength under loadings of short duration, it creeps continuously under sustained loads, with the result that large deformations accumulate with time. Creep rupture may occur under loads which are too small to produce instantaneous failure. Strength and deformation resistance increase as bulk density increases and temperature decreases. The material can be destroyed by melting, and it can be evaporated even at low temperatures. Dry snow from the upper layers of ice sheets is highly porous and has good insulating properties, but it is also highly permeable. It is friable, and resists compressive loading better than tensile loading. Finally, small snow and ice particles sinter easily on mutal contact, so that an aggregation of freshly comminuted snow "sets up" and gains strength with time.

General Modes of Utilization

There are three broad ways in which snow can be utilized as a structural material: (i) it can be used in place to form pads and pavements or walls and roofs of excavations, (ii) it can be cut out in blocks and built up like masonry, (iii) it can be pulverized mechanically and cast like concrete. In each of these three cases the snow can be used alone or in combination with other materials.

The use of snow as a medium for excavation is treated in other sections, and a separate monograph is devoted to the construction of snow pavements. These topics are touched upon briefly here for the sake of completeness.

Structural Dependence on Snow in Excavations

Unsupported excavations can be made in dense snow with virtually no danger of sudden collapse, but fairly rapid creep deformation occurs under the stresses imposed by self-weight body forces, even at shallow depths. Nevertheless, unsupported excavations provide cheap shelter, and they can have a working life of several years if there is sufficient clearance to allow for deformation. When rigid linings are installed in snow excavations, the snow ceases to play a beneficial structural role.

The excavation techniques used in snow are described in the previous section, and deformation of excavations in snow is discussed in CRSE Monograph III-A2c.

Snow Block Masonry

Snow blocks are produced easily with unskilled labor and simple tools. They are sawn out of the snow mass with hand saws, chain saws, or other cutters, preferably to standard dimensions. For volume production it ought to be possible to devise some kind of "cooky cutter." The blocks should be as big as possible, with maximum size for easy lifting and handling setting the limit. The blocks should be of equant form (length, breadth and height of similar size) to avoid undue breakage during handling. If they are cut from snow which is strongly stratified, the blocks preferably should be cut and laid so that the original stratification remains horizontal.

The main uses for snow block masonry are in walls, pillars, platforms and domes.

Walls

Snow block walls can be used for the construction of temporary housing, hangars for light aircraft, garages or workshops. These buildings are usually roofed by beams of timber or metal sheeted with wood, metal or fabric. Snow block wall can also be used as snow fences or as protective barriers in high winds. Snow block walls ...n scour holes at the base are useful for protecting aircraft which have to be picketed out in severe blizzards. Snow block walls have also been used as bulkheads in trenches and tunnels.

If the surface snow at a site is not strong enough for preparation of building blocks, denser and therefore stronger material can be found a few feet below the surface. Spoil deposited by rotary snowplows yields very strong blocks. A convenient size for snow blocks is about 18 in. by 18 in. by 12 in. thick. Low walls built with blocks of this size need be of only single thickness, and no bond is required (except at corners). Snow blocks are laid dry, but they may be "rubbed" to a neat fit during laying. On completion of a wall the joints can be "pointed" with snow if the weather is warm (cold snow does not stick). Within a few days the blocks adhere firmly to each other as a result of sintering, even at quite low temperatures.

The strip footing for a snow block wall may consist of boards laid in a trench 12 to 18 in. deep, or the snow blocks may be laid directly on the undisturbed snow in a shallow trench, provided that snow is sufficiently strong. A dense natural snow weighs about 25 to 30 lb/ft^3 so that the pressure on the base of a 10-ft wall is no more than 300 lb/ft^2. As long as the ambient temperature remains well below freezing and the footing is shielded from strong sunshine, stresses of this magnitude give only small settlement rates.

Roof beams should not be laid directly across the top of snow block walls, but should bear onto fairly rigid capping beams to avoid stress concentrations.

Figure 34 shows a circular snow house with snow block walls under construction on the Greenland Ice Cap. This was a USA SIPRE experimental building. It had an internal diameter of 22 ft with walls 9 ft high and 2 ft thick. The roof was made up from specially prepared aluminum beams and segmented sheets radiating from a jackable central column, which also acted as a ventilation duct. Even after it became deeply buried by snow, this snow house remained accessible and usable for a number of years.

Snow houses have been used for various purposes by a number of polar expeditions, roofs usually being improvised from lumber and tarpaulins. An aircraft hangar was built with snow blocks during the 1939-41 Byrd Antarctic Expedition.

Figure 34. Circular snow house with snow block walls under construction on Greenland Ice Cap.

Pillars and platforms

Snow blocks can be used to build short, thick columns for temporary support of loads. Unconfined snow pillars creep noticeably under their own weight, but they can act as useful temporary props as long as the imposed axial stress can be kept down to about 10 lb/in.² Squat columns and platforms can be built up from snow blocks to form instrument towers, lighting standards, beacons and storage areas. Hollow columns can be used to extend emergency exits and ventilation stacks for undersnow installations.

A fair idea of the strength and deformation resistance of snow pillars under various conditions can be gained from the results of unconfined compression tests.

Domes

The dome is a structural form well adapted to snow construction. It is, in fact, the classical form of snow architecture. The strength and stability of a snow dome under short-time loading is adequately demonstrated by the ability of a small igloo, or snow house (built from hand-cut blocks), to withstand the weight of three men standing on its roof.

The traditional Eskimo igloo, or snowhouse, is built with blocks of natural cohesive snow cut and shaped with a large knife. The blocks are laid in a single spiral course of steadily reducing horizontal diameter, and the crown of the dome is closed with a specially shaped king block. The method of construction is illustrated in Figure 35. Domes up to 20 ft in diameter can be built in this way.

Igloos provide excellent emergency shelter; they are warmer and more spacious than trail-type tents and the wall insulation is such that inside temperatures can be raised appreciably by human body heat and even by candles.
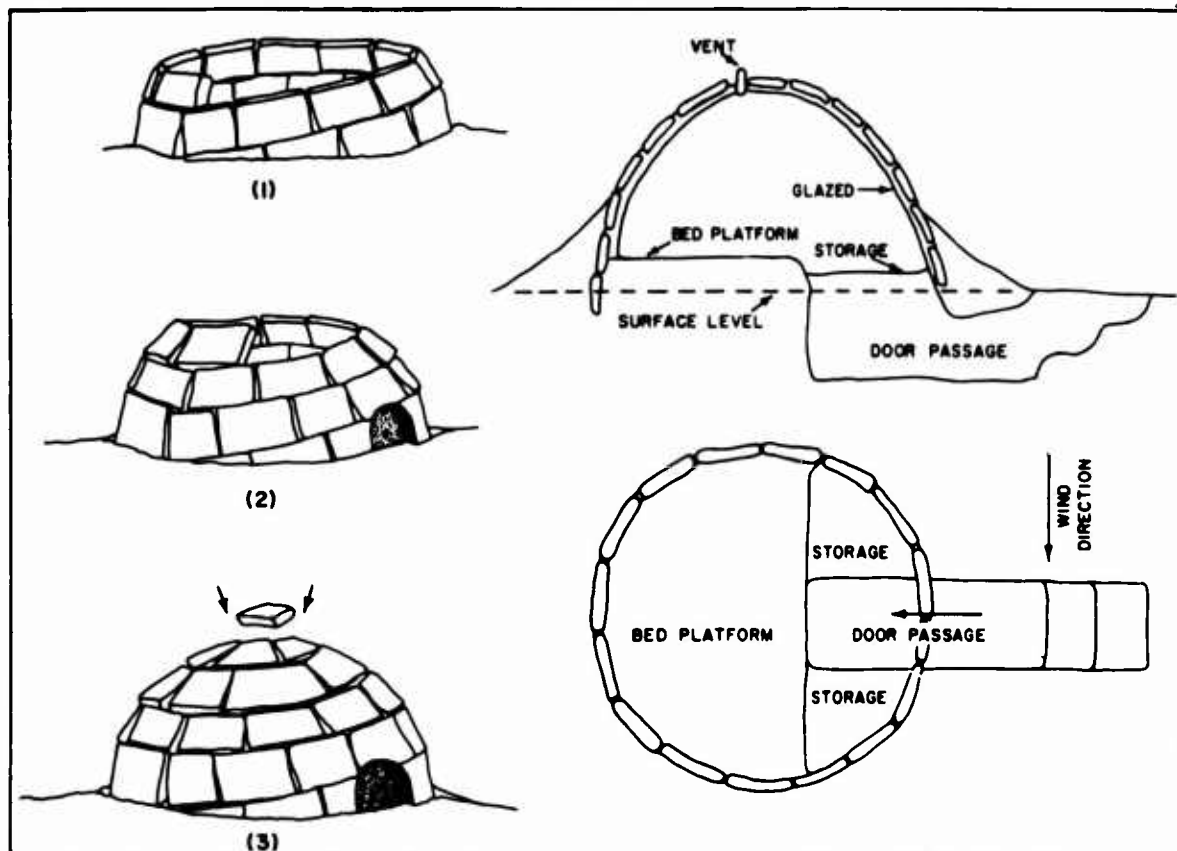
Figure 35. Construction of Eskimo igloo, or snowhouse.

Structural Elements of Cast Snow

Structural elements of snow, such as walls, beams, arches, domes, abutments and columns can be formed by milling snow with a rotary snow plow and depositing the resulting pulverized material in or over formwork. The milled snow settles under gravity to a moderately high initial density (≈ 0.55 g/cm^3), bonding and gaining strength with time after it is deposited. Unless temperatures are very low, formwork can be stripped within a day or so of casting.

The only machine which has been used to any extent for milling and blowing cast snow is the Swiss Peter Snowmiller, described on p. 27. This is an expensive item of heavy equipment, requiring trained operators, and its provision at a remote site is justified only when a big job is to be undertaken. It is, however, a versatile machine and is also used for precise excavation in snow. In the cut-and-cover method it has a twofold role: it excavates the trenches and casts processed snow to form the roof arches. When cast snow is being placed, long throws should be avoided, particularly on windy days, as the winnowing action may leave the placed aggregate deficient in fines.

Walls

Walls of cast snow have been used to build simple surface structures. These include a rectangular, flat-roofed building and a covered access to an undersnow station. Roofing is formed from light corrugated metal arch or from joists or rafters covered with light sheeting of metal, wood, or even cloth.

a. During construction

b. Completed building
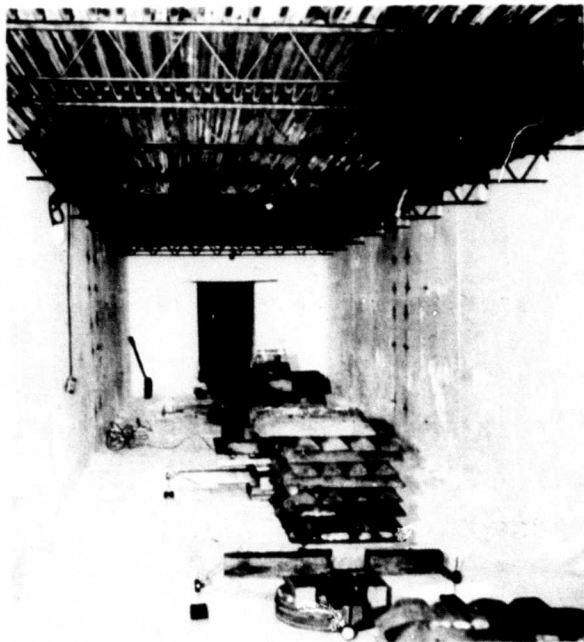
c. Interior view

Figure 36. Construction of small surface building from cast snow.

Figure 37. Entrance to an undersnow complex on the Greenland Ice Cap. The snow walls were built by dumping milled snow between plywood forms.

·Walls can be built either by placing snow between double forms, in the way that concrete would be placed, or by piling snow against a single form. Unless a special casting chute is available, it is hard to blow milled snow directly from the plow into double forms without spilling material over a wide area. Hence the snow is deposited in the forms by a bucket loader or similar device, which 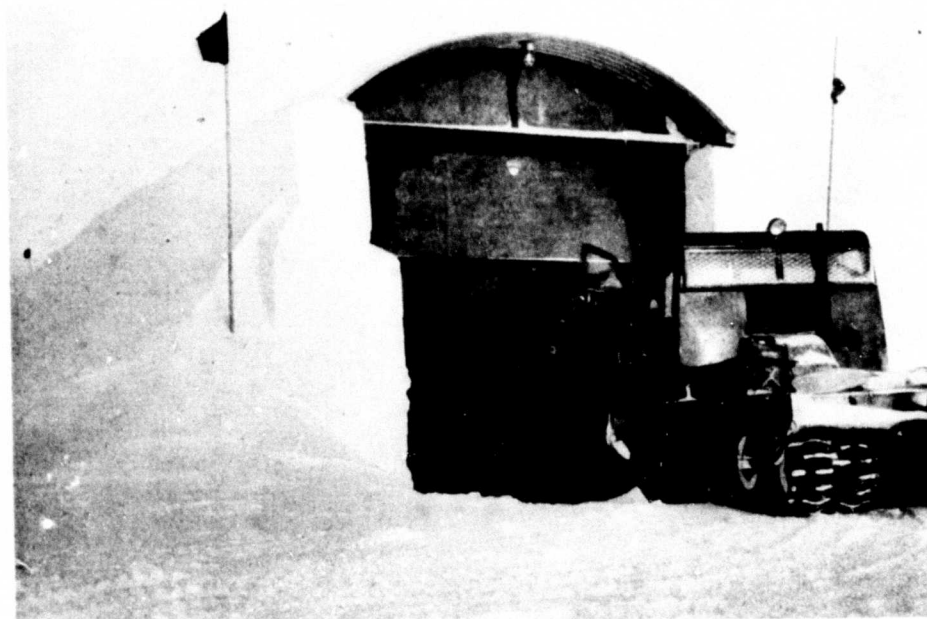scoops from a conveniently placed pile of freshly milled snow. The snow may be compacted by a hand-operated vibratory compactor. Snow can be placed against well-braced single forms simply by pushing it there with a blade. Forms can be stripped after 8 to 12 hr when temperatures are mild, say above −20C (about −5F), allowing early re-use of the formwork.

Snow walls of this kind are made quite thick − 3 to 4 ft. Walls which face the sun should be built with sufficient thickness to allow for "rotting" of a surface layer a few inches thick. Wall foundations may be either compacted natural snow or redeposited milled snow.

Figure 36 illustrates the construction of a small surface building from cast snow. Figure 37 shows the covered entrance for a subsurface camp.

Pillars

Cast snow can be used to form useful load-bearing columns and a variety of pillars and platforms by placing it inside light permanent forms, which provide lateral restraint during subsequent deformation.

Beams

Tests on beams cut from age-hardened Peter snow were made in Greenland by USA SIPRE.[17] The beams cut were 8 ft long and the depth of section (rectangular) tapered from 18 to 6 in.; the width was 18 in. Pairs of beams were slid out from opposite sides of an 8-ft-wide trench and deformation was observed for a pair of these cantilevers butted at the center joint and for a pair cemented together with wet snow at the center to form a simple haunched beam.

The beam uncemented at the center attained a steady deformation rate of 0.028 in./hr under its own weight. The beam cemented at the center was given a uniformly distributed load of 12 in. of Peter snow and it settled to a steady deformation rate of 0.023 in./hr at its midpoint. The ambient temperature was not recorded. At these rates of deformation the weekly sag would be about 4 in. and failure could be expected to ensue in a short time.

Long-term creep tests were made on beams of plain and reinforced Peter snow in Antarctica.[15] Beams 1 ft × 1 ft × 8 ft long were formed by blowing milled snow directly into casting beds with a Peter Junior hand-maneuvered rotary plow (Fig. 38). Some of the forms contained only Peter snow, while in others excelsior wood fiber was dispersed within the Peter snow. Pretensioned fibrous cords were cast into the upper and lower thirds of one beam, and another beam had expanded metal mesh laid in the upper and lower thirds. After casting, the beams were screeded and left to sinter for 4 weeks before the forms were stripped.

The 275-lb beams of unreinforced Peter snow and the beam "reinforced" with cord were too fragile to withstand handling, but the beams reinforced with excelsior and with expanded metal were sufficiently robust to survive rough rides on a forklift tractor. The reason for the failure of the beam reinforced with cord was lack of bonding between cord and snow. A second set of unreinforced beams broke in handling, and tests finally had to be made on 6-in. × 6-in. × 4-ft unreinforced beams.

For testing, the beams were simply supported on roller-mounted abutments and allowed to deform under their own weight at temperatures which fluctuated between −20C and −30C. Deformation rate was relatively high for the first 5 weeks, but it gradually slowed to a sustained steady rate. The beam reinforced with expanded metal sagged 1.3 in. in 10 months, but its secondary creep rate for midpoint deflection was only 0.51 in./yr. The beam containing a liberal addition of excelsior

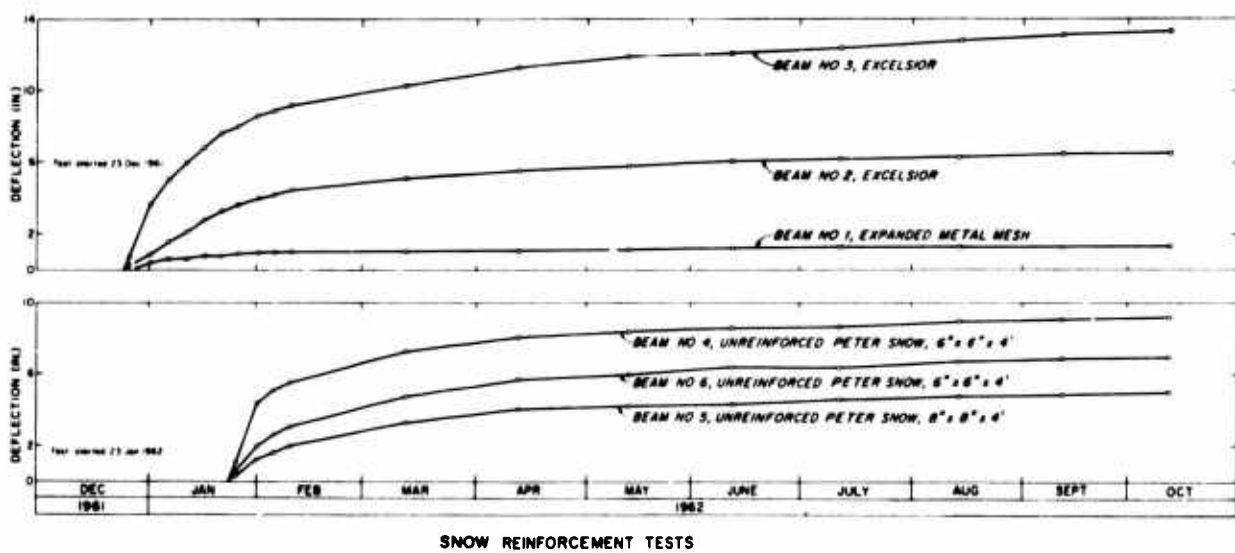Figure 38. Peter Junior rotary plow casting milled snow into beam forms.

SNOW REINFORCEMENT TESTS

Figure 39. Deformation as a function of time for small beams of Peter snow. Above, reinforced beams 1 ft × 1 ft × 8 ft. Below, unreinforced beams. (Mellor and Hendrickson[15].)

deflected 6.5 in. in 10 months and had a secondary creep rate of 2.9 in./yr. The beam containing a smaller concentration of excelsior deflected 13.3 in. in 10 months and had a secondary creep rate of 5.6 in./yr. Figure 39 shows deformation of reinforced and unreinforced beams of Peter snow in Antarctica.

The performance of the small unreinforced beams cannot be compared directly with that of the large reinforced beams, but on the basis of elastic theory the deflections of the small beams would have to be multiplied by a factor of 4 for comparison with the deflections of the large beams. The actual deflections of the small beams were from 5 to 9 in. in 9 months and the average secondary creep rate was 2.4 in./yr.

On the basis of these results it appears that unreinforced beams of snow are of no structural value whatsoever, but beams and slabs of milled snow reinforced with suitably bonded mesh possess significant resistance to creep and fracture. Small snow houses could probably be roofed with reinforced snow.

Arches

The arch is well suited to the peculiar properties of snow, and cast snow (Peter snow) arches have been used successfully for roofing trenches.[20] The snow arch, being a compressive structure, has a reasonable resistance to high short-time loading, such as that due to a vehicle driven over it. It can also tolerate extended periods of deformation before the intrados sags to the level of the springings: a beam spanning the same abutments would have its soffit at this level when placed and would soon sag further.

The springings (abutments) for a snow arch are formed by laying a pad of milled snow prior to trench excavation and then cutting the trench through the pad to leave shoulders of high-strength processed snow. Metal arch forms are attached at the springings by means of pegs and rails (Fig. 40),[20] and milled snow is blown over the forms by a rotary plow until the desired crown thickness has been reached. After the age-hardening process has developed intergranular bond in the snow, the forms are stripped. Inflated cylindrical bags may be used as an alternative to metal arch forms (Fig. 41).

Snow arches have been cast over circular-arc forms and over slightly pointed forms. Observations, though not conclusive, suggest that a pointed arch is more stable than a circular one. Whatever the arch profile, the rise to span ratio should be high – 0.3 to 0.4 or more. Arch thicknesses have been chosen empirically so far, since stresses in the visco-plastic arch are indeterminate. Experience has shown that crown thicknesses from 2 to 3 ft are adequate for cast Peter snow arches of 9- to 14-ft span.

The arch shown in Figure 42a (p. 51) had a crown thickness of 3½ ft and a pointed profile. It had a natural snow cover of 3½ ft after 10½ months, but virtually no distortion of the arch had occurred. The rise-to-span ratio was 0.35. The flatter circular arch of Figure 42b (p. 52) showed less satisfactory behavior during a one-year working life. Its rise-to-span ratio was 0.26. Both arches were located at the USA SIPRE Site II in northern Greenland.

The 9-ft-span snow arch in Figure 42c, which was used to roof a tunnel at Byrd Station, Antarctica, had a very small rise-to-span ratio and it sagged significantly over a 2-year period. The profiles show how the arch springings were thrust apart as the arch deformed.

All existing experience indicates that small-span cast-snow arches, when properly designed and constructed, provide perfectly adequate and highly economical roofing for unheated trenches.

Figure 40. Removable formwork for casting arch roofs on trenches with milled snow (Waterhouse[30]).
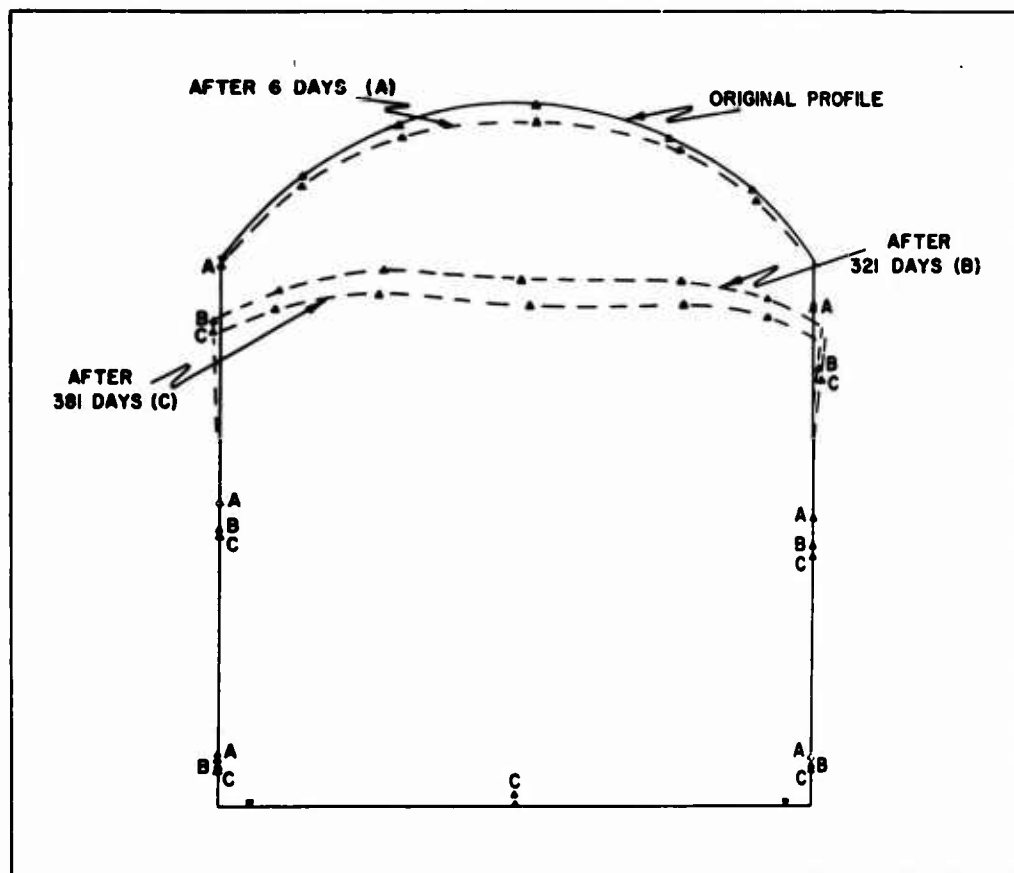
Figure 41. Inflated cylindrical airbags placed between prepared abutments in preparation for the casting of snow arch.
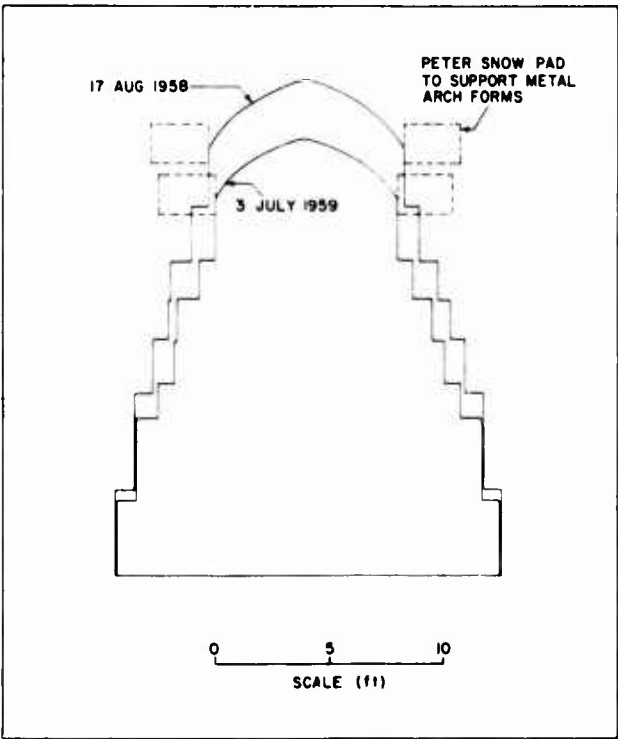
a. Rise-to-span ratio: 0.35 (USA SIPRE Site II, Greenland)

Figure 42. Arch forms in snow.

b. Rise-to-span ratio: 0.26 (USA SIPRE Site II, Greenland)

Figure 42 (Cont'd). Arch forms in snow.

Domes*

Domes 16 to 36 ft in diameter have been built by casting snow from a Peter miller over inflatable hemispherical domes of neoprene-coated nylon (Figure 43), and over nylon-fabric-covered geodesic framework of aluminum. The forms were removed when the snow had been allowed to harden (about 12 hr after casting).
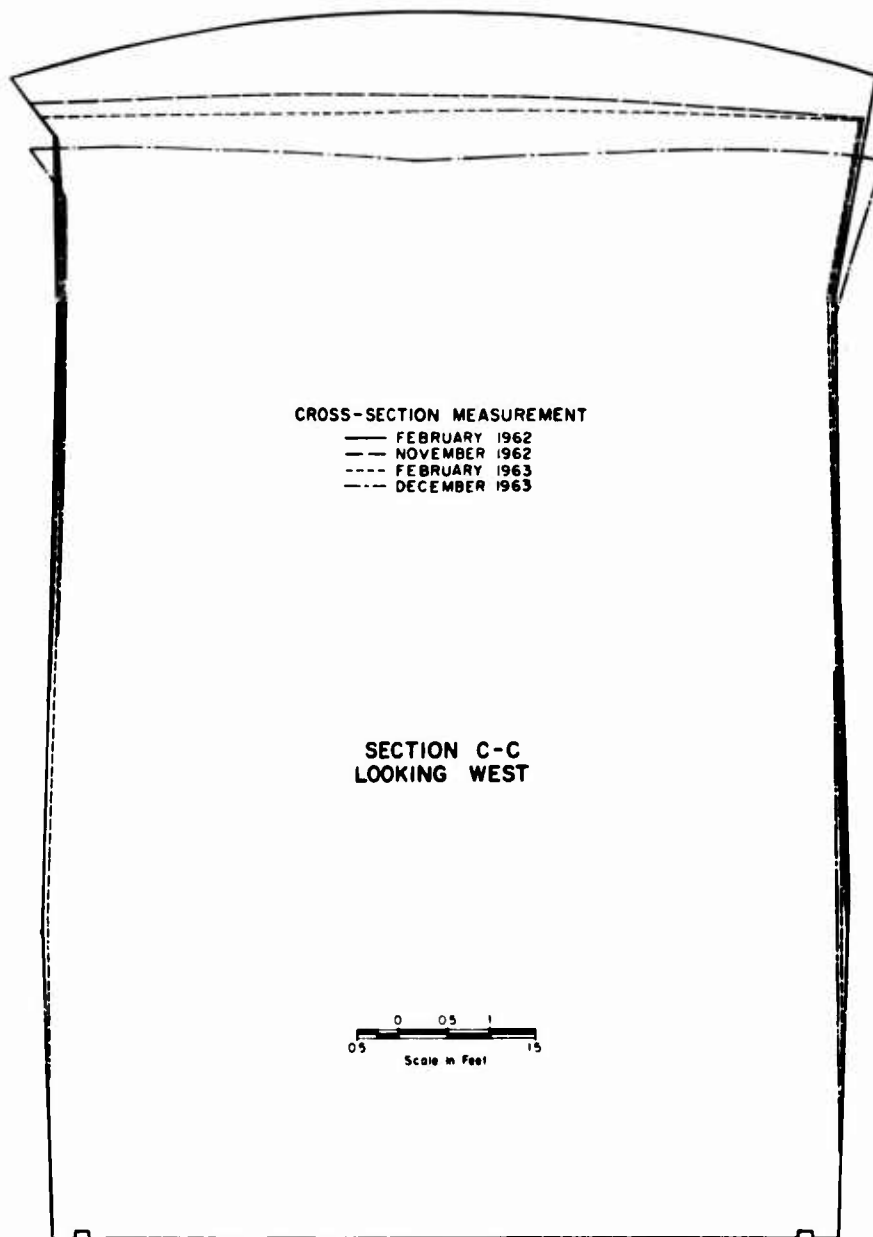
No long-term observations on cast-snow domes are available, but the crown of a 20-ft-diam Peter-snow dome with a crown thickness of 10 in. sank 6 in. in the first 5 days after the forms were stripped; it is expected that subsequent rate of deformation would be very much lower.

Domes are best cast in pits or trenches cut in the natural snow. This gives sound foundation material and effects economies in Peter snow by retaining the cohesionless backfill, which would otherwise settle to a gentle angle of repose. Buried domes do not generate surface snowdrifts and are protected against high air temperatures and solar radiation.

Abutments

Snow abutments are an important consideration in the design of roofing systems for cut-and-cover trenches, which may be spanned by metal, timber, snow, or composite members. The high

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*Personal communication by R.W. Waterhouse, Project Engineer.

CROSS-SECTION MEASUREMENT
——— FEBRUARY 1962
— — NOVEMBER 1962
---- FEBRUARY 1963
—·— DECEMBER 1963

SECTION C-C
LOOKING WEST

c. Very small rise-to-span ratio (Byrd Station, Antarctica)

Figure 42 (Cont'd). Arch forms in snow.

local stresses at points where the roof load is transmitted to the trench walls accelerate deformation and may even cause shear failure. Thus it is desirable to form shoulders of high-strength processed snow.

To prepare Peter snow abutments for the roof arch of an 8-ft-wide cut-and-cover trench the plow makes initial passes over a lane 12 ft wide, milling to a depth of 3 ft and replacing the comminuted snow in its wake. After the pad of Peter snow has had several hours to "set-up," the main excavation cut, 8 ft wide, is made down the center of the 12-ft pad so that 2-ft-wide shoulders are left on each side of the trench.

Figure 43. Casting snow dome over inflated form. (Photo by R.
Waterhouse.)

Figure 44. Arch abutments for a cut-and-cover snow tunnel. The abutments
have been prepared and supports for the arch forms have been fitted. The
formwork supports are acting as rails for a target trolley to guide the plow
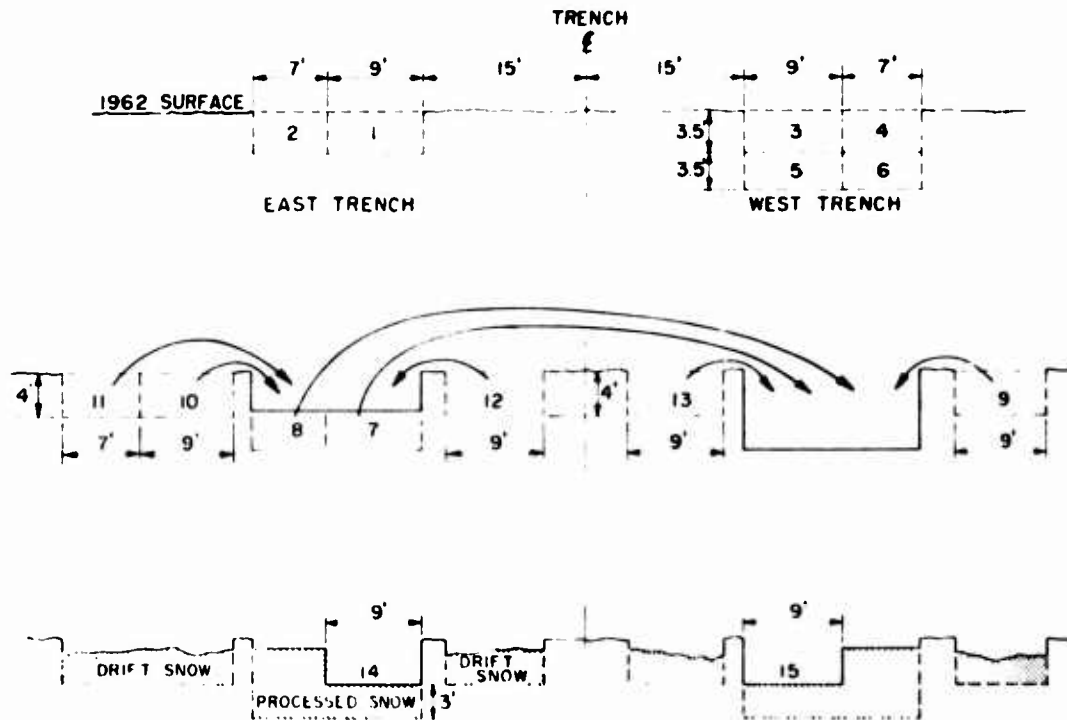during subsequent cutting. (Photo by R. Waterhouse.)

Figure 45. Cut-and-fill procedure for preparation of milled snow abutments for 30-ft-wide trench. (Tobiasson and Rissling[19]).

If the natural snow 3 ft below the surface is judged to have adequate strength for abutments, the plow makes an initial cut 12 ft wide by 3 ft deep, but the milled snow is ejected to the side of the cut. The main trenching cut is then made down the center of the resulting trough and the abutments take the form of stepped shoulders, each 3 ft deep and 2 ft wide.

The preparation of cast snow abutments on wide trenches demands more complicated cutting sequences for efficient operation. Figure 45 gives an illustration of the procedure followed when abutments were being prepared prior to the cutting of a 30-ft-wide trench at Camp Century in Greenland.

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13 ABSTRACT

This monograph is the 2nd of a series of 5 on Snow Engineering: Construction. It covers the site investigations and laboratory tests in connection with construction on a permanent snowfield, and then deals with the technology of excavation and building where snow is almost the only constructional material. The author draws heavily on the work of the Cold Regions Research and Engineering Laboratory (CRREL) in the development of Camp Century and other projects on the Greenland ice sheet and shows the application of the techniques to Antarctic Research Stations.

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